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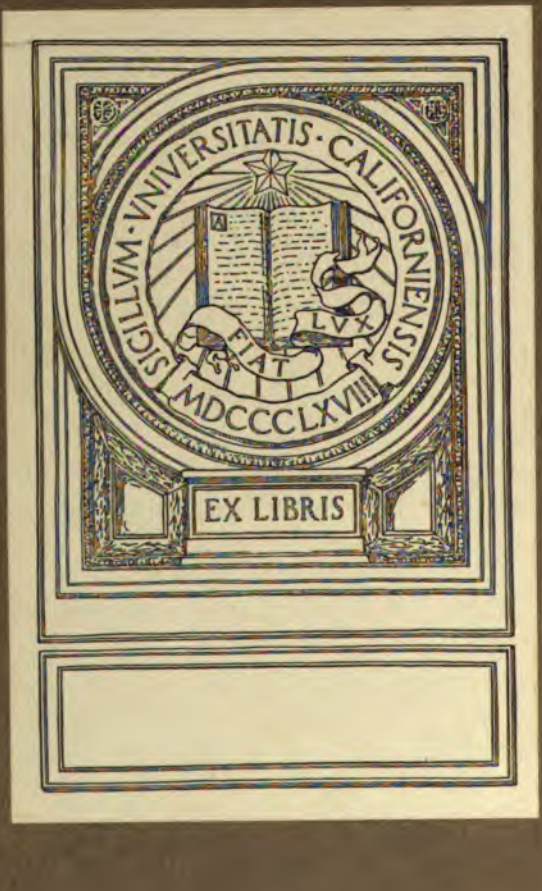

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DYNAMO-ELECTRIC MACHINERY:

A MANUAL FOR STUDENTS OF ELECTROTECHNICS.

BY

SILVANUS P. THOMPSON, D.Sc., B.A., F.R.S.;

PRINCIPAL OF, AND PROFESSOR OF PHYSICS IN, THE CITY AND GUILDS OF LONDON TECHNICAL COLLEGE, FINSBURY;
LATE PROFESSOR OF EXPERIMENTAL PHYSICS IN UNIVERSITY COLLEGE, BRISTOL;
MEMBER OF THE INSTITUTION OF ELECTRICAL ENGINEERS;
VIC[redacted]OCIETY OF LONDON;
DE PARIS;
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PREFACE

TO THE FOURTH EDITION.

IN this fourth edition, which has been very largely rewritten, there are several features which distinguish it from its predecessors.

The great development of public electric lighting during the past five years has necessitated the construction of very large dynamos suitable for central stations. Of the established types of these machines detailed descriptions are given.

A number of Plates have been added, some of them being scale-drawings of recent forms of machines.

The invention of alternate-current motors of many novel types, depending on the production of multiphase alternate currents, has claimed a special chapter.

A chapter has been added on the theory of armature winding.

No pains have been spared to ascertain the most approved practice in the construction of armatures, commutators, and other details requiring combined mechanical and electrical knowledge and experience. A chapter has been added on dynamo design.

Transmission of power by electrical means also claims a short special chapter.

Some remarks on the management of dynamos have been embodied at the end of the work.

It would have been impossible to do justice to the present development of the subject but for the co-operation of the electrical engineers and engineering firms who are leading the advance. For such co-operation the author's thanks are gratefully given. And in particular he tenders his acknowledgment to the following, who have specially aided him by furnishing him with drawings and statistical data: Mr. C. E. L. Brown (late of the Oerlikon Works, Zürich); Mr. Gisbert Kapp; Mr. W. B. Esson (of Messrs. Paterson and Cooper); Mr. Mordey (Brush Electric Engineering Co.); Mr. T. Parker (Electric Construction Corporation); Mr. Albion T. Snell (General Electric Traction Co.); Messrs. W. T. Goolden and Co.; Mr. S. Z. de Ferranti; Messrs. Blakey, Emmott and Co.; The Gülcher Electric Co.; Messrs. Ernest Scott and Co.; Messrs. J. H. Holmes and Co.; Messrs. Siemens Bros.; Messrs. Mather and Platt; Messrs. R. E. Crompton and Co.; Messrs. S. Schuckert and Co.; Messrs. J. G. Statter and Co.

For the use of cuts the author is indebted to various of the above-named firms, and also to the publishers of the following journals: *The Electrician*, *Electrical Review*, *Industries*, and *La Lumière Électrique*. To the publishers of the *Electrical Engineer* (N.Y.) for Plate XIII.

The author is indebted to his colleague, Professor Perry, F.R.S., for the use of some of his notes in the preparation of Chapter XV.

His former chief assistant, Professor R. Mullineux Walmsley, has again kindly rendered help in reading proofs of several of the new chapters.

To his late pupil, Mr. Walter Hawkings, the author is indebted for valuable help in preparing drawings, particularly those dealing with armature winding.

Heavy as the task is of adequately presenting the principles and practice of a department of science which has undergone such an enormously rapid development, that task has been lightened in three directions by the circumstance that three fellow-workers in science have lately devoted themselves to expounding special branches of it. Professor Ewing, of whose researches in magnetism an all too brief account has been given in this book, has prepared a treatise on magnetism which is on the very eve of publication. Professor Fleming has already published the first half of a treatise on the

Alternate Current Transformer, and the second half will soon appear. Mr. Gisbert Kapp's work on Electric Transmission of Power has already commanded a wide acceptance. There has been, therefore, the less necessity to extend those chapters in the author's book which deal with these topics, though they have been carefully brought up to date.

Want of space has precluded the author from treating as fully as he would have desired the topic of central station machinery. This has assumed three different types in England, Germany, and America. In England, engineers have developed special forms of high-speed engine to be coupled direct to the dynamo. In Germany practice has taken the inverse course of designing huge slow-speed dynamos for attachment direct to engines of older type. Either of these methods is, in the author's opinion, preferable to the American practice of building high-speed dynamos and low-speed engines, and then connecting them by belts running over pulleys.

It would be difficult to discover any scientific subject which more thoroughly illustrates the principle of action and reaction than does this of dynamo-electric machinery. In every department of the subject the essential thing to be understood is a reaction of some sort. In the rotating armature of the dynamo the very production of the current sets up an opposing drag, and the work of generating the current is done by driving the machine against this mechanical reaction. In the motor the very production of motion sets up an opposing electromotive-force which tends to stop the supply of current. In the transformer, the current which is set up by the magnetic changes in the core, tends to oppose those changes. In the self-induction coil the changes of magnetism which result from the impressed waves of current tend to destroy those waves. In the alternate-current motor the moving part tends so to move as to annul the changes of magnetic polarity which urge it round. In the classical law of magneto-electric action, formulated by Lenz, it is declared that an induced current is always such that by virtue of its electromagnetic effect it tends to stop the motion which generated it. To this we have added (p. 589) a converse and equally general law for electric motor action, namely, that the motion produced is always such that by virtue of the magneto-electric inductions which it sets up it tends to stop the current. Both are but forms of a still more general law applicable to every electromagnetic system, namely, that every action on such a system which, in producing a change in its configuration or state involves a transfer of energy, is resisted by reactions tending to preserve unchanged the configuration or state of that system.

The subject of dynamo-electric machinery is, however, something more than a mere branch of universal dynamics; it constitutes to day a very active department of constructive engineering. To set forth this practical side of the subject in a manner useful to engineers has been the author's continual aim. Being intended for the instruction of electrical engineers in the technicalities of their craft the book will now take its place in the series of Finsbury Technical Manuals.

S. P. T.

New Year's Eve, 1891.

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DYNAMO-ELECTRIC MACHINERY.

CHAPTER I.

INTRODUCTORY.

A dynamo-electric machine is a machine for converting energy in the form of mechanical power into energy in the form of electric currents, or vice versâ, by the operation of setting conductors (usually in the form of coils of copper wire) *to rotate in a magnetic field.* This definition is framed to include all machines, the action of which is dependent on the principle of magneto-electric induction, discovered by Faraday in 1831.

Every dynamo-electric machine is, however, capable of serving two distinct functions, the converse of one another. When supplied with mechanical power from some external source of power, such as a steam-engine, it furnishes electric currents. When supplied with electric currents from some external source such as a voltaic battery, it furnishes mechanical power. On the one hand the dynamo serves as a *generator*, on the other hand as a *motor*. All dynamos, however, belong to one of two great sub-divisions, being distinguished, according to the nature of the current which they are to supply, whether *direct* (*i.e.* uni-directional in flow) or *alternating* (*i.e.* rapidly reversing the direction of the flow). We shall therefore have to consider four classes of machines—(*a*) direct-current dynamos; (*b*) alternate-current dynamos, or, briefly, alternators; (*c*) direct-current motors; (*d*) alternate-current motors. In general every dynamo, whether intended for use as a generator or as motor, consists of two essential parts, a *field-magnet*, usually a massive, stationary structure of iron surrounded by coils of insulated copper wire, and an *armature*, a peculiarly arranged system of copper conductors, usually wound upon the periphery of a ring, drum, or disk, fixed upon a shaft whereby rotation can be imparted mechanically. There are also special devices for receiving the electric currents from the armature and imparting them to the electric circuit, or *vice versâ*, known as *collectors* or *commutators*, attached to the armature and rotating with it, and collecting *brushes*, constituting sliding circuit-connexions, which press upon the moving surface of the collector or commutator.

The function of the field-magnet is to provide a *magnetic field* of great extent and intensity; that is to say, to provide an enormous number of lines of magnetic force in the space wherein the armature conductors are to revolve. It must consequently consist of a large and well-designed, and therefore powerful, magnet or electromagnet, having its poles so shaped that the magnetic lines that issue from them shall be utilised in the armature space. The magnetic field and the magnetic properties of iron are dealt with in Chapter VI.; the fundamental principles of the magnetic circuit, including the designing of field-magnets, are dealt with in Chapters VII., VIII., and XVI.

The function of the armature is to rotate in the magnetic field, whilst carrying electric currents in its copper coils or conductors.

It must be remembered that there is a two-fold action between a conducting wire (forming part of a circuit) and a magnetic field. *Firstly*, if the conducting wire is forcibly moved across the magnetic field (so as to cut across the magnetic lines), electric currents are generated in the conductor, and a mechanical effort is required to move the conductor. This action, discovered by Faraday, is termed "magneto-electric induction." In every case the induction or generation of currents necessitates the application of mechanical power and the expenditure of energy. This is the principle of the dynamo used as a generator. *Secondly*, if the conducting wire, while situated in the magnetic field, is actually conveying an electric current (from whatever source) it experiences a lateral thrust, tending to move it forcibly, parallel to itself, across the magnetic lines, and so enables it to exert power and to do work. This action, which is the converse of the former, is the principle of the dynamo used as a motor. In the first case power is required to drive the armature; in the second, the armature rotating becomes a source of power. If we have the magnetic field, and supply power to drive the rotating conductor, we get the electric currents; if we have the magnetic field and supply the electric currents to the conductor, it rotates and furnishes power. Whether the machine be used as generator or as motor, the magnetic field must be present: hence the most important point in theory is the theory of the magnetic field. As every dynamo will work (at least theoretically) either as generator or as motor, it should be possible to frame a general theory for any machine serving either of these two converse functions. For the sake of simplicity, however, these two fuctions will be separately considered in the present work.

The mathematical theory of the dynamo is, indeed, complex, and takes different forms for its expression in the various classes of machine now included under the one name of "dynamo." The progress recently made in the theoretical treatment of magnetic problems has simplified matters so much that it is now possible to predict from the construction and dimensions of a dynamo its electrical output under given conditions of speed and load. The theory of alternate-current machines is different in many points from that of machines which are to furnish continuous currents. The theory of the dynamo, then, which will be developed in the present work, will not be a general mathematical theory. The aim will be to deal with physical and experimental rather than mathematical ideas, though of necessity mathematical symbols must be used here as in every kind of engineering work. A physical theory of the dynamo is not new, though none of any great completeness had been given[1] prior to the appearance of the author's lectures at the *Society of Arts* in 1882.

There are, in fact, three distinct methods of dealing with the principles of the dynamo: (1) a physical method, dealing with the lines of magnetic force and with currents, in which these quantities are made, without further inquiry into their why or how, the subjects of the arguments; (2) an algebraical method, founded upon the mathematical laws of electric induction and of theoretical mechanics; and (3) a graphical method, based upon the possibility of representing the action of a dynamo by a so-called "characteristic" curve, in the manner originally devised by Dr. Hopkinson, and subsequently used by Frölich, Deprez, and others.

These three methods present three aspects of the same thing. The number of lines of magnetic force, with which we deal in Chapters VI. and VII., may be expressed by a certain length of line geometrically, or by the symbol N algebraically, or they may be represented pictorially by a mere illustration. What some people write N for, other people indicate by drawing a line of a certain length in a certain direction. We approximate, in fact, toward understanding the whole truth by various processes: sometimes by algebra; sometimes by geometry; sometimes by magnetic diagrams; and each of these processes is of value in its turn.

It will be our aim first briefly to develop a general physical theory, applicable to all the varied types of dynamo-electric machines. Then we shall at once plunge into the most fundamentally important matters; the principle of the magnetic circuit; the magnetic properties of iron; the design of the magnetic parts of dynamos, and the like. After this will come the theory of armature winding, and practical modes of construction. This will be followed by a general descriptive

[1] See J. M. Gaugain, *Annales de Chimie et de Physique*, 1873; Antoine Breguet, *Annales de Chimie et de Physique*, 1879; Du Moncel, *Exposé des Applications de l'Électricité*, vol. ii.; Niaudet, *Machines Électriques*; Dredge's *Electric Illumination*; Schellen, *Die Magneto- und Dynamo-elektrischen Maschinen* (3rd edition, 1883).

account of the various types of machines, and by various matters of theoretical interest. The direct-current motor will be considered after the direct-current generator. The special topics of the alternate-current dynamo, the alternate-current transformer, and the alternate-current motor, are treated in fuller detail than in any of the previous editions of this work.

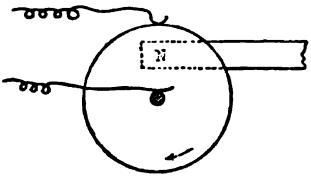
Before, however, proceeding to the general theory of the dynamo, it will be expedient to introduce a few historical notes.

CHAPTER II.

HISTORICAL NOTES.

FARADAY'S discovery of the magneto-electric induction of currents was made in the autumn of 1831, and communicated, on Nov. 24th, to the Royal Society in a paper printed in the *Philosophical Transactions*, and reprinted in the beginning of the first volume of Faraday's *Experimental Researches in Electricity*. His first experiments related to the production of induced currents in a coil by means of currents started or stopped in a neighbouring coil; from these he went on to currents generated in a coil moved in front of the poles of a powerful steel magnet. Upon thus obtaining electricity from magnets he attempted to construct "a new electrical machine." A disk of copper, 12 inches in diameter (Fig. 1), and about one-fifth of an inch in thickness, fixed upon a brass axle, was mounted in frames, so as to allow of revolution, its edge being at the same time introduced between the magnetic poles of a large compound permanent magnet, the poles being about half an inch apart.[1] The edge of the plate was well amalgamated, for the purpose of obtaining a good but movable contact, and a part round the axle was also prepared in a similar manner. Conducting strips of copper and lead to serve as electric collectors, were prepared, so as to be placed in contact with the edge of the copper disk; one of these was held by hand to touch the edge of the disk between the magnet poles. The wires from a galvanometer were connected, the one to the collecting-strip, the other to the brass axle; then on revolving the disk a deflexion of the galvanometer was obtained, which was reversed in direction when the direction of the rotation was reversed. "Here, therefore, was demonstrated the production

FIG. 1.



FARADAY'S DISK DYNAMO.

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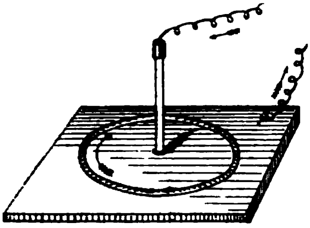
[1] *Experimental Researches*, i. 25, art. 85. This piece of apparatus is still preserved at the *Royal Institution*. It was shown in action by the author of this work at a lecture at the Royal Institution delivered April 11th, 1891.

of a permanent current of electricity by ordinary magnets." These effects were also obtained from the poles of electromagnets, and from copper helices without iron cores. Several other forms of magneto-electric machines were tried by Faraday.

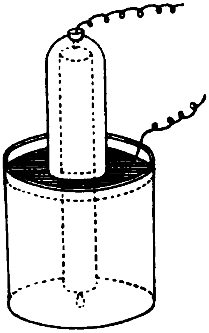
In one,[1] a flat ring of twelve inches external diameter, and one inch broad, was cut from a thick copper plate, and mounted to revolve between the poles of the magnet, two conductors being applied to make rubbing contact at the inner and outer edge at the part which passed between the magnetic poles. In another,[2] a disk of copper, one-fifth of an inch thick, and only 1½ inch in diameter (Fig. 2), was amalgamated at the edge, and mounted on a copper axle. A square piece of sheet metal had a circular hole cut in it, into which the disk fitted loosely, a little mercury completed communication between the disk and its surrounding ring. The latter was connected by wire to a galvanometer; the other wire being connected from the instrument to the end of the axle. Upon rotating the disk in a horizontal plane, currents were obtained though the earth was the only magnet employed.

FIG. 2.



FARADAY'S TEETOTUM APPARATUS.

FIG. 3.



FARADAY'S ROTATING COPPER CYLINDER.

Faraday also proposed a multiple machine[3] having several disks, metallically connected alternately at the edges and centres by means of mercury, which were then to be revolved alternately in opposite directions. In another apparatus[4] a copper cylinder (Fig. 3), closed at one extremity, was put over a magnet, one half of which it enclosed like a cap, and to which it was attached without making metallic contact. The arrangement was then floated upright in a narrow jar of mercury, so that the lower edge of the copper cap touched the fluid. On rotating the magnet and its attached cap, a current was sent through wires from the mercury to the top of the copper cap. In another apparatus,[1] still preserved at the Royal Institution, a cylindrical bar magnet, half immersed in mercury, was made to rotate, and generated a current, its own metal serving as a conductor. In another form,[2] the cylindrical magnet was rotated horizontally about its own axis, and was found to generate currents which flowed from the middle to the ends, or *vice versâ*, according to the rotation. In yet another machine (Fig. 4) constructed by Faraday some time later,[3] a simple rectangle of copper wire, attached to a frame, was rotated about a horizontal axis placed east and west, and generated alternate currents, which could be collected by a simple commutator.

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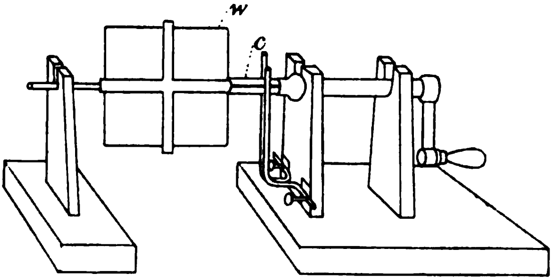
[1] *Experimental Researches*, i. art. 135.

[2] *Ib.*, art. 155.

[3] *Ib.*, art. 158.

[4] *Ib.*, art. 219.

FIG. 4.



FARADAY'S ROTATING RECTANGLE.

Within a few months machines on the principle of magneto-induction had been devised by Dal Negro,[4] and by Pixii.[5] In the latter's apparatus a steel horseshoe magnet, with its poles upwards, was caused to rotate about a vertical shaft, inducing alternate currents in a pair of bobbins fixed above it, and provided with a horseshoe core of soft iron. Later, in 1832, Pixii produced, at the suggestion of Ampère,[6] a second machine, provided with commutators to rectify the alternating currents. Further improvements were made by Ritchie[7] and Watkins.[8] In 1833 appeared the machine of

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[1] *Experimental Researches*, i. art. 220. [2] *Ib.*, art. 222. [3] *Ib.*, art. 3192.

[4] *Phil. Mag.* [3] i. 45, July 1832 (an oscillatory apparatus).

[5] *Ann. Chim. Phys.* l. 322, 1832. [6] *Ann. Chim. Phys.*, li. 76, 1832.

[7] *Phil. Mag.* [3] viii. 455; [3] x. 280, 1837; and *Phil. Trans.*, ii. 318, 1833.

[8] *Phil Mag.* [3] vii. 107, 1835.

Saxton,[1] and two years later that of Clarke;[2] both having the steel horseshoe magnet a fixture, and having as a revolving armature an electromagnet consisting of a pair of bobbins wound upon a simple horseshoe of iron. Clarke's machine possessed many original details, including a special form of commutator for giving short, sharp currents for physiological purposes. In it the armature rotated, not opposite the ends, but in close proximity to the flat faces of the magnet. In Saxton's machine, which was shown to the British Association at Cambridge in 1833, the armature was rotated opposite the polar ends, and consisted of four coils. Von Ettingshausen,[3] in 1837, brought out a very similar alternate-current machine, with a special device by which the alternate currents could be cut out. Poggendorff,[4] in 1838, devised a special mercury-cup commutator for Saxton's machine, to make the currents less discontinuous.

Other improvements in detail were made by Petrina,[5] who improved the commutator; Jacobi,[6] who pointed out the importance of using short cores for the armatures; Sturgeon,[7] who placed a shuttle-wound coil longitudinally between the limbs of a horseshoe magnet, and who also invented the simple two-part commutator or "unio-directive discharger," as he termed it; Stöhrer,[8] who showed how to construct a six-pole machine with six bobbins in the armature; Ritchie,[9] who employed tubular cores and a double winding; and Pulvermacher,[10] who in 1849 proposed the use of thin laminæ of iron as core-plates. Woolrich,[11] in 1841, devised a multipolar machine for electroplating, having twice as many rotating coils as magnet-poles. Wheatstone[12] began his improvements in 1841, with a machine in which for the first time the armature coils were so grouped as to give a really continuous current (Fig. 5). For this purpose five armatures, each consisting of a pair of short parallel cylindrical coils with iron cores, and each having a simple split-tube commutator, were arranged in a row along a single shaft, with six compound steel magnets between them, the five armatures being so set that they came successively into the position of greatest activity, no two of them being commuted at the same instant. They were connected in series with one another by wires, which joined the positive brush—a brass spring—of one to the negative brush of the next. In 1845 Wheatstone[1] and Cooke patented the use of electromagnets instead of steel permanent magnets in such machines. In 1848 Jacob Brett[2] made the important suggestion of causing the current developed in the armature by the permanent magnetism of the field-magnets to be transmitted through a coil of wire surrounding the magnet, so as to increase its

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[1] *Phil. Mag.* [3] ix. 360, 1836.

[2] *Phil. Mag.* [3] ix. 262, 1836; x. 365, 455, 1837; and Sturgeon's *Annals of Electricity*, i. 145.

[3] Gehler's *Physikalisches Wörterbuch*, ix. 122, 1838.

[4] *Pogg. Ann.*, xlv. 385, 1838.

[5] *Pogg. Ann.*, lxiv. 58, 1845.

[6] *Pogg. Ann.*, lxix. 194, 1846.

[7] *Annals of Electricity*, ii. 1, 1838. See also Sturgeon's *Scientific Researches*, p. 252; also *Phil. Mag.*, vii. 231, 1835.

[8] *Pogg. Ann.*, lxi. 417, 1884; lxxvii, 467, 1849.

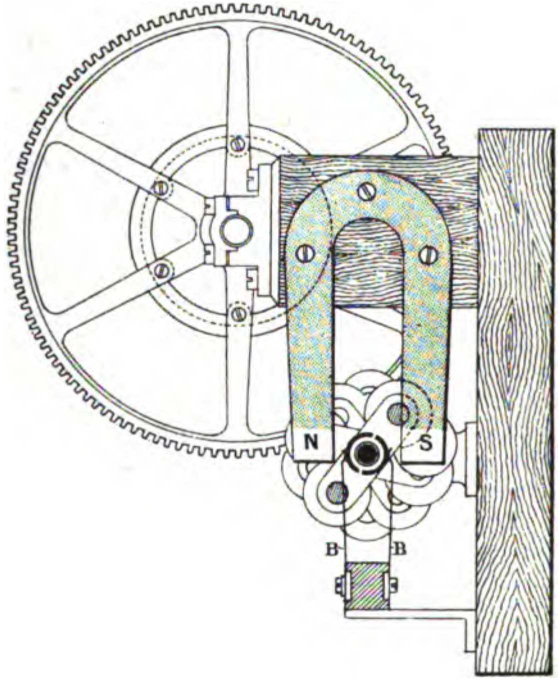
[9] Specification of Patent, 14,899 of 1849.

[10] *Loc. cit.*

[11] See also Specification of Patent, 9431 of 1842.

[12] Specification of Patent, 9022 of 1841.

FIG. 5.



WHEATSTONE'S CONTINUOUS-CURRENT MACHINE.

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[1] Specification of Patent, 10,655 of 1845.
[2] Specification of Patent, 12,054 of 1848.

action. This suggestion, which appears to be the first suggestion of the principle of the self-exciting dynamo, was independently made in 1851 by Sinsteden,[1] who appears to have had full knowledge of the fact, investigated by Müller, that steel is capable of receiving a temporary magnetization not greatly inferior to that of wrought iron, and far in excess of that which it can permanently retain. Sinsteden's researches were numerous and important, relating to the best width of polar surface to employ, to the use of pole-pieces, and to the lamination of armature cores, for which purpose he employed, in 1849, iron wire bundles. A quite different type of machine was suggested independently by Ritchie,[2] by Page,[3] and by Dujardin,[4] in which neither field-magnet nor armature rotated; the coils in which the currents were to be induced were wound upon polar extensions of the field-magnets, and the induction was produced by rotating in front of them pieces of soft iron, which set up rapid periodic variations in the magnetic field. Machines on this same principle were later devised by Holmes, Henley, Wheatstone, Wilde, Sawyer, by the author of this work, and by Kingdon.

Nollet,[5] in 1849, devised an alternate-current machine, in the construction of which he was joined by Van Malderen; and after the death of Nollet this was developed, with the aid, first of Holmes, then of Masson and Du Moncel, into the "Alliance"[6] machine, which, from the year 1863, did good service in the lighthouses of France. Holmes continued to perfect his work, and produced a fine machine,[7] which in 1857 received high commendation from Faraday. The great machine of Holmes shown in the International Exhibition of 1862, was a continuous-current machine, with a large commutator and rotating rollers for brushes; the bobbins, 160 in number, were arranged on the peripheries of two wheels, each about 9 ft. in diameter. There were sixty horseshoe magnets arranged in three circles, each presenting radially forty poles. In 1867 Holmes remodelled his machine, making the field-magnets more powerful in proportion, and leaving the induced currents uncommuted; and in 1869 he introduced the principle of diverting the current from a few of the armature coils, through a commutator, to excite the field-magnets. This period was one of great activity. In 1855 Hjorth[1] patented a remarkable machine, having for its field-magnets a compound arrangement of a permanent magnet to provide initial currents, and powerful electromagnets to be excited up by the currents generated by the machine itself.

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[1] *Pogg. Ann.*, lxxxiv. 186, 1851. For Sinsteden's other researches see *Pogg. Ann.*, lxxvi. 29, 195 and 524, 1849; lxxxiv. 181, 1852; xcii. 1 and 220, 1854; xcvi. 353, 1855; cxxxvii. 290 and 483, 1869.

[2] *Phil. Mag.* [3] x. 280, 1837.

[3] *Annals of Electricity*, 489, 1839.

[4] *Comptes Rendus*, xviii. 837, 1844; xxi. 528, 892, 1881.

[5] See Specification of Patent, 13,302 of 1850. See also Douglass in *Proc. Inst. Civil Engin.*, lvii. 1878–9.

[6] See Du Moncel's *Exposé des Applications de l'Électricité*, i. 361. Also see Le Roux, *Bulletin de la Société d'Encouragement*, 1868.

[7] See Douglass, *loc. cit.* Also Specifications of Patents, 573 of 1856, 2060 of 1868, and 1774 of 1869.

C. W. Siemens[2] in 1856 provisionally patented the famous shuttle-wound longitudinal armature, invented by Werner Siemens. In 1859,[3] he made the suggestion that the core only need rotate, the coils being fixed in grooves in the pole-pieces of the field-magnets. Wilde,[4] of Manchester, embarked on a remarkable series of researches from 1861 to 1867. Beginning with small apparatus for telegraphic purposes, he was led in 1863 to devise an apparatus having a shuttle-wound Siemens armature between the poles of a powerful electromagnet, the coils of which were traversed by currents furnished by a small auxiliary machine—with shuttle-wound armature and permanent magnets—mounted upon its summit. In 1866 and 1867 Wilde devised alternate-current machines, of which the latest had a number of bobbins mounted on the periphery of a disk rotating between two opposite crowns of alternately polarized field-magnets—a type which survives to the present day. These machines, originally separately excited by currents from a small magneto machine, were made self-exciting, in 1873, by diverting through a commutator the currents induced in one or more of the armature bobbins. The principle of using the whole or part of the machine's own currents to excite the requisite magnetism of its field-magnets was by this time becoming recognized. As mentioned above, Brett, Sinsteden, and Hjorth had all made use of this principle. In 1858, Johnson,[5] patent-agent for a foreign inventor, states; "It is proposed to employ the electromagnet in obtaining induced electricity, which supplies wholly or partially the electricity necessary for polarizing the electromagnets, which electricity would otherwise be required to be obtained from batteries or other known sources." In July, 1866,

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[1] Specifications of Patents, 12,295 of 1848, 2199 of 1854, 2198 of 1854, 806 of 1855, 807 of 1855, and 808 of 1855.

[2] Specification of Patent, 2017 of 1856. See W. Siemens, *Pogg. Ann.*, ci. 271, 1857.

[3] Specification of Patent, 512 of 1859.

[4] Specifications of Patents, 299, 858, 1994 and 2997 of 1861; 516 and 3006 of 1863, 1412 and 2753 of 1865, 3209 of 1866, and 824 of 1867.

[5] Specification of Patent, 2670 of 1858.

Murray[1] stated that he had connected in series with the armature some coils wound on the field-magnets of his magneto machine and recommended the adoption of this plan. In October 1866, Moses G. Farmer[2] wrote to Wilde of Manchester, describing his success in winding main circuit coils upon the field-magnets of his machine, so as to cause it to excite its own magnets. In November 1866, Baker[3] stated that the secondary currents from the revolving magnets might be applied to magnetize the fixed magnets. In December of the same year C. and S. A. Varley[4] filed a Provisional Specification for a machine having electromagnets only, which apparatus, however, required before using to have given to it a small amount of permanent magnetism since the inventors state that "the bobbins become slightly magnetized in their passage between the poles of the permanent magnets." This, it must be conjectured, was given to it by passing an electric current through the coils of the electromagnets; a device which reappears in another machine patented by the same inventors in June, 1867, and again in another by O. and F. H. Varley in 1869. The electromagnets of the 1867 machine were wound with two separate circuits, supplied alternately with currents from two commutators which received the currents from two separate pairs of coils. Mr. S. A. Varley continued, in 1868, and 1871, to patent magneto-electric generators. In 1876 he returned to the self-exciting method, employing a multiple armature in which the principle was applied of cutting out each coil in succession during the rotation. In this machine also there were two windings on the field-magnets, one of greater resistance than the other, both of which were led to the lamp, the circuit of greater resistance being always closed. It was not, however, clear that this method of double winding was what is now understood as "compound winding,"[5] until such was laid down with legal authority by a Scotch judge fifteen years later. Returning to the self-exciting principle, we find that on January 17th, 1867, Dr. Werner Siemens[6] described to the Berlin Academy a machine for generating electric currents by the application of mechanical power, the currents being induced in the coils of a rotating armature by the action of electromagnets, which were themselves excited by the currents so generated. In this machine also initial permanent magnetism was to be given by sending a preliminary current through the coils from a battery. To mark the importance of this departure Siemens coined the name *dynamo-electric machine*, which now, in the shortened form of *dynamo*, has become the familiar term for all these electric machines driven by mechanical power, whether self-excited or not. On the same day that this discovery was announced to the Royal Society, February 14th, 1867, a paper was read by Sir C. Wheatstone,[1] making an almost identical suggestion; but with this difference, that whilst Siemens proposed that the exciting coils should be in the main circuit, in series with the armature coils, Wheatstone proposed that they should be connected as a shunt. A self-exciting machine without permanent magnets had indeed been constructed for Wheatstone by Mr. Stroh in the summer of 1866.

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[1] See *Engineer*, p. 42, July 20, 1866.

[2] *Proc. Lit. and Phil. Soc. of Manchester*, vi. 107.

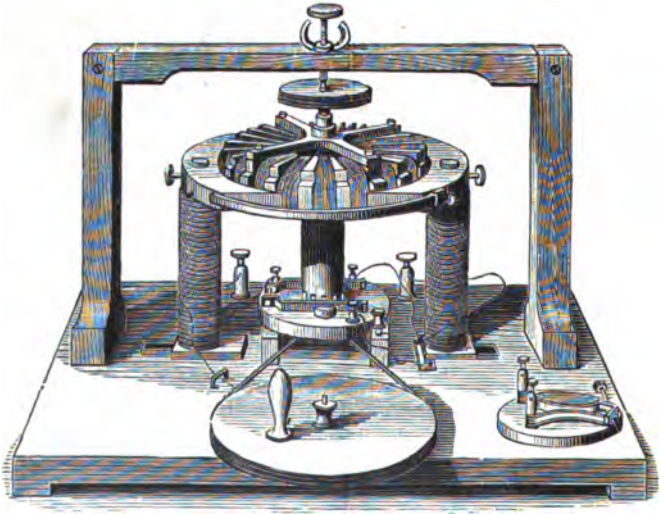
[3] Specification of Patent, 3039 of 1866.

[4] Specification of Patent, 3394 of 1866. Other Varley Specifications are 1755 of 1867, 315 of 1868, 131 and 1150 of 1871, 4905 of 1876, 270 and 4435 of 1877, 4100 of 1878.

[5] See *Phil. Mag.* [4] xlv. 439, 1873.

[6] *Berliner Berichte*, Jan. 1867; *Proc. Roy. Soc.*, Feb. 14, 1867; Specification of Patent, 261 of 1867; and *Pogg. Ann.*, cxxx. 332, 1867.

FIG. 6.



PACINOTTI'S MACHINE, WITH RING ARMATURE.

In 1867 Ladd[2] exhibited a self-exciting machine having two shuttle-wound armatures, a small one to excite the common field-magnet, a large one to supply currents for electric light.

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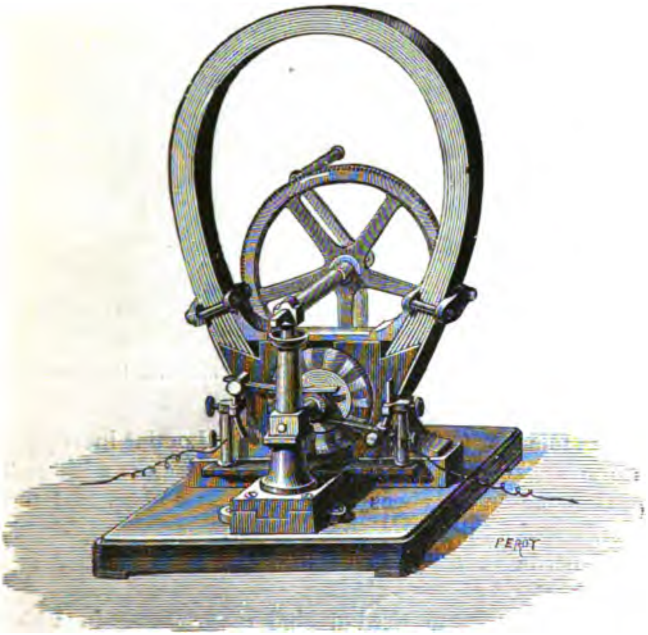
[1] *Proc. Roy. Soc.*, Feb. 14, 1867.

[2] *Phil. Mag.* [4] xxxiii. 544, 1867.

[3] *Nuovo Cimento*, xix. 378, 1865.

Meantime the question of procuring continuous currents, with less fluctuation in their strength, had come up, and had received from Pacinotti[3] an answer, which, though it fell into temporary oblivion, is now recognized as of great merit. He devised a machine, first described in 1864, having as its armature an electromagnet in the form of a ring, the core consisting of a toothed iron wheel, between the teeth of which the coils were wound in sixteen separate sections. He denominated this a "transversal electromagnet." The coils being joined up in a closed circuit, if at any point a current was introduced, it flowed both ways through the coils to some other point where it was taken off by a return wire. By the device of leading down connections, at sixteen different points around the ring, to sixteen insulated pieces of metal arranged as a commutator, it was possible to cause magnetic poles to appear in the ring at any desired points. The principle of winding a continuous coil in separate symmetrical sections around a ring, or other figure of revolution, was independently invented, in 1870, by

FIG. 7.

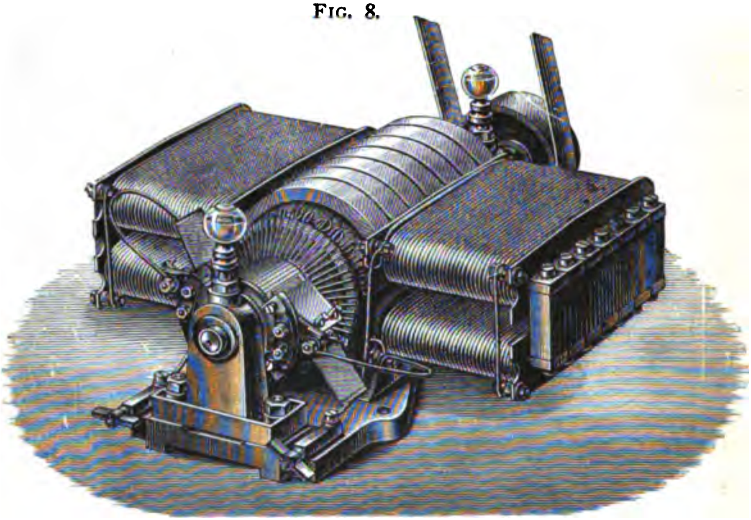


GRAMME MACHINE, LABORATORY PATTERN.

OF THE

Gramme,[1] whose ring had no teeth, and was entirely overwound with wire. By winding an armature with a number of such symmetrically grouped coils which pass successively through the magnetic field, currents can be obtained that are practically steady. The introduction of the Gramme armature was at once recognised as marking an important step, and it gave a fresh impetus to invention. In 1873 von Hefner Alteneck[1] modified the longitudinal armature of Siemens by covering it with windings spaced out at symmetrical angles to secure the same advantage of continuity, and Lontin[2] in 1874 sought to perform a like transformation upon an armature with radiating poles. Gramme and Siemens both devised many special forms of machines, some furnishing alternating currents,[3] others continuous currents. Bertin in 1875, Brush in 1879, and Siemens,[4] in 1880, revived the method of shunt-winding.

Fig. 8.



Siemens's Dynamo with von Hefner Alteneck's Drum-wound Armature.

In 1878 Pacinotti[6] devised a kind of armature in which the conductors took the form of a flat disk or fly-wheel. Brush[1] also introduced his famous dynamo embodying the principle of open-coil working. He also introduced the simultaneous use of a shunt and a series winding for the purpose of enabling the machine to do either a large or a small amount of work. Another open-coil machine was introduced in 1880 by Elihu Thomson and E. J. Houston,[2] of Philadelphia. About the same time Weston[3] devised several forms of dynamo, and in particular developed shunt-wound machines. Many other American inventors produced dynamos, amongst them Edison,[4] who began in 1878, with a machine in which the motion was oscillatory instead of rotatory, a device which had been tried by Dujardin,[5] in 1856, by Siemens,[6] in 1859, by Wilde,[7] in 1861, and abandoned. Edison himself abandoned it in 1879 for a form of machine having a modified Hefner-Alteneck armature and an elongated shunt-wound electromagnet. In 1881, he produced a disk dynamo on the same lines as Pacinotti's disk. The same year saw a revival of alternate-current machines in the forms devised by Sir W. Thomson[8] (and independently by Ferranti) and Gordon.[9]

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[1] *Comptes Rendus*, lxxiii. 175, 1871, and lxxv. 1497, 1872; and Specification of Patent, 1668 of 1870.

[2] Specification of Patent, 2006 of 1873. A similar suggestion had been thrown out the previous year by Worms de Romilly.

[3] Specifications of Patents, 473 of 1875, 386 and 3264 of 1876.

[4] Specification of Patents, Gramme, 953 of 1878; Siemens, 3134 of 1878.

[5] *Phil. Trans.*, March 1880.

[6] *Nuovo Cimento* [3] i., 1881.

About this time multipolar dynamos began to come into favour, the multipolar drum armature introduced by Lord Elphinstone[10] and Mr. Vincent, and the multipolar ring, independently, by Schuckert, Gramme, Gülcher, and Mordey.[11] Lord Elphinstone in particular drew attention to the importance of perfecting the magnetic circuit, though, for purely mechanical reasons, his machine soon became obsolete. Hopkinson[12] showed how greatly the performance of a dynamo was improved by improving and making more compact its magnetic circuit, whilst Crompton[13] amidst a number of improvements in detail, showed the advantage of increasing the cross-section of iron in the armature core. Meantime theoretical considerations had led

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[1] Specification of Patent, 2003 of 1878.

[2] Specification of Patent, 315 of 1880.

[3] Specifications of Patents, 4280 of 1876, 1614 and 2194 of 1882.

[4] Specifications of Patents, 4226 of 1878, 2402 of 1879, 1240 and 2954 of 1881, and 2052 of 1882.

[5] See Du Moncel's *Exposé des Applications*, i. p. 372.

[6] Specification of Patent, 512 of 1859.

[7] Specification of Patent, 924 of 1861.

[8] Specification of Patent, 5668 of 1881.

[9] Specifications of Patents, 5536 of 1881 and 2871 of 1882.

[10] Specifications of Patents, 332 of 1879, and 2893 of 1880.

[11] Specification of Patent, 400 of 1883.

[12] Specification of Patent, 973 of 1883.

[13] Specifications of Patents, 2618 and 4810 of 1882, and 4302 of 1884.

Marcel Deprez,[1] in 1881, to the conclusion that a dynamo driven at a certain critical speed ought to be able to distribute currents at a constant potential if its field-magnets were provided with a second coil to furnish from a battery or other source an independent and constant auxiliary excitation. This was almost immediately followed by the general adoption of the so-called compound winding, for the purpose of obtaining a self-regulating dynamo, this advance being the subject of conflicting rival claims. Since 1883 the chief progress made has been in details of design and mechanical construction. Large multipolar machines for continuous currents have been designed by Siemens and Halske, by C. E. L. Brown, and others, and are in successful operation. Disk dynamos have also been introduced by Desroziers and by Fritsche. Large alternating machines have been constructed by Ganz, by Ferranti, and by Mordey; the latter's machine having a notable improvement in the use of a single compact magnetic circuit for the field-magnet. The latest novelty is the multiphase alternate-current machine, of which the most important example is the type constructed by Brown for the transmission of power by three-phase currents from Lauffen to Frankfort.

The other branch of the subject, that of the electric motor, goes back to the discovery by Faraday[2] in 1821 of electromagnetic rotation, and the invention, in 1823, by Barlow,[3] of his rotating wheel. The earliest electric motors in which the principle of attraction by an electromagnet was applied were those of Henry,[4] in 1831, and of Dal Negro,[5] in 1832, and these were followed in 1833 and 1834 by the motors of Ritchie[6] and of Jacobi,[7] and in 1837 by that of Davenport.[8] Many other inventors devised machines of this kind, some of the most famous being Page[9] in the United States, Davidson in Scotland, Wheatstone[10] in England, Froment[11] in France, and Pacinotti[12] in

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[1] *La Lumière Électrique*, December 3, 1881, and January 5, 1884.

[2] Journal of *Royal Institution*, September 1821.

[3] Barlow, *On Magnetic Attraction* (1823), 279; and *Encyclopædia Metropolitana* (1824), iv. art. *Electromagnetism*, 36.

[4] *Silliman's Journal*, xx. 340, 1831. Also Henry, *Scientific Writings* (1886), i. 54.

[5] *Annali delle Scienze Lombardo-Veneto*, March 1834.

[6] *Phil. Trans.* 1833 [2], 318.

[7] *L'Institut*, lxxxii. Dec. 1834.

[8] See *Annals of Electricity*, ii. 1838, *Encyclopædia Britannica* (ed. vii.), art. *Voltaic Electricity*, 687.

[9] *Silliman's Journal*, xxxiii. 1838; and [2] x. 344 and 473, 1850.

[10] Specification of Patent, 9022 of 1841.

[11] See *Cosmos*, x. 495, 1857, and *La Lumière Électrique*, ix. 193, June 1883.

[12] *Nuovo Cimento*, xix. 378, 1865.

Italy. The discovery that the action of a dynamo is the simple converse of that of the motor, and that the same machine can serve either function, appears to have been made by Jacobi,[1] in 1850, though it only came into general recognition somewhat later. It was certainly known in 1852, for in the fourth edition of Davis's Magnetism, published at Boston, an apparatus, described as a "revolving electromagnet" (a slight modification of Ritchie's motor) is shown, on page 212, as a motor, and the same apparatus is again shown on page 268 as a generator, accompanied by the remark that "any of the electromagnetic instruments in which motion is produced by the mutual action between a galvanic current and a steel magnet may be made to afford a magneto-electric current by producing the motion mechanically. Walenn[2] explicitly stated the same point in 1860; and it was also stated by Pacinotti in 1864. The principle of transmitting power from one dynamo used as a generator to another used as motor is claimed for Fontaine and Gramme, as a discovery made in 1873, when such an arrangement was shown at Vienna. It has been noisily claimed, but without the shadow of reason, for Marcel Deprez[3], who did not, however, discover it until 1881. In 1882 Ayrton and Perry made the important discovery of the automatic regulation of motors, to run with constant velocity, by methods akin to, but the converse of, those adapted for making dynamos self-regulating. Since that date, the improvements made in continuous current motors, though great, have been in mechanical perfection of design and detail. The alternate-current dynamo does not make a convenient alternate-current motor, as it is not self-starting. When once started, however, it runs in absolute synchronism with the generator. Ferraris, in 1888, made the important suggestion to drive a motor by two independent alternate currents of similar period, but differing in phase, thus producing a rotating magnetic field. The same suggestion came independently from Nikola Tesla, who first put such motors into practical form. Many forms of rotary-field motors have since been devised; one of the most remarkable being that of Dolivo Dobrowolsky—the so-called *dreh-strom* motor—used in the Lauffen-Frankfort demonstration.

The theory of the dynamo dates back to the investigations of Weber[4] and of Neumann[5] respecting the general laws of magneto-electric induction, followed by Jacobi's[1] calculations and experiments respecting the performance of an electric motor, by Poggendorff's[2] and Koosen's[3] investigations of the theory of the Saxton magneto-machine, and by the researches of Lenz,[4] Joule,[5] Le Roux,[6] and of Sinsteden.[7] These researches were followed at a long interval by those of Favre,[8] followed by silence for twenty years, broken only by the pregnant, but almost totally forgotten, little paper in which Clerk-Maxwell[9] laid down a theory for self-exciting machines. On the revival of electric lighting the theory of the dynamo was again studied, important contributions being made by Mascart,[10] Hagenbach,[11] von Waltenhofen,[12] Hopkinson,[13] Herwig,[14] Meyer and Auerbach,[15] and Joubert.[16] The latter founded the modern theory of alternate-current machines. Hopkinson[17] devised the method of representing, by a curve, the relation between the current and the working electromotive force of the machine; such curves, under the name of "characteristics," subsequently formed the basis of the theoretical researches of Marcel Deprez.[18] In 1880 Frölich[19] began a series of investigations both experimental and theoretical, that led to equations of remarkable simplicity, if not of more than approximate value, and in 1883 Clausius,[20] adopting Frölich's fundamental expression for the law of the electromagnet, evolved with great elaboration a theory in which all the various secondary effects arising in generators were taken into account—a theory which he later extended to the case of motors.

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[1] *Mémoire sur la Théorie des Machines électromagnétiques.*

[2] Specification of Patent, 2587 of 1860.

[3] Specification of Patent, 2830 of 1882. See *Journ. Soc. Telegr. Engineers*, xii. 301, 1883.

[4] *Elektrodynamische Maasbestimmungen* (1846).

[5] *Berliner Berichte*, p. 1, 1845; and p. 1, 1847.

[1] *Pogg. Ann.*, li. 370, 1840; lxix. 181, 1846; and *Krönig's Journal*, iii. 377, 1851. Also *Ann. Chim. Phys.* [3] xxxiv. 451, 1852.

[2] *Pogg. Ann.*, xlv. 390, 1838.

[3] *Pogg. Ann.*, lxxxv. 226; and lxxxvii. 386, 1852.

[4] *Pogg. Ann.*, xxxi. 483, 1834; xxxiv. 385, 1835; and xcii. 128, 1854.

[5] *Annals of Electricity*, iv. v. 1839–40; *Phil. Mag.* [3] xxiii. 263, 347, and 435, 1843.

[6] *Ann. Chim. Phys.* [3] l. 463, 1857.

[7] *Pogg. Ann.*, lxxxiv. 181, 1851.

[8] *Comptes Rendus*, xxxiv. 342, 1853; xxxix. 1212, 1854; xlvi. 337, 658, 1858.

[9] *Proc. Roy. Soc.*, Mar. 14, 1867; and *Phil. Mag.* [4] xxxiii. [474], 1867.

[10] *Journal de Physique*, vi. 204, 297, 1877; and vii. 89, 1878.

[11] *Archives des Sciences Physiques*, lv. 255, March 1876; and *Pogg. Ann.*, clviii. 599, 1876.

[12] *Wiener Berichte*, lxxx. 601, 1879.

[13] *Proc. Inst. Mech. Engineers*, 238, 1879, and 266, 1880.

[14] *Wied. Ann.*, viii. 494, 1880.

[15] *Wied. Ann.*, viii. 494, 1879.

[16] *Ann. de l'École Normale*, x. 131, 1881; and *Journal de Physique* [2] ii. 293, 1883.

[17] *Proc. Inst. Mech. Engineers*, 238, 1879.

[18] *Comptes Rendus*, xcii. 1152, 1881; and *La Lumière Électrique*, xv. 1, 1885.

[19] *Berl. Berichte*, 962, 1880; *Electrotechnische Zeitschrift*, ii. 134, 170, 1881; vi. 128, etc., 1885; and ix., Nov. 1888.

[20] *Wied. Ann.*, xx. 353, 1883; xxi. 385, 1884; *Phil. Mag.* (5) xvii. 49 and 119, 1884.

In 1886 John and Edward Hopkinson[1] published a remarkable paper, developing, from theoretical considerations respecting the induction of magnetism in a magnetic circuit of given form and materials, a theory of the dynamo, the perfection of which may be judged by the fact that its use, as now extended by various workers, enables the performance of a machine to be predicted with extraordinary accuracy from the design as laid down in the working drawings. Other contributions to the theory of dynamos have been made by Sir W. Thomson[2] (windings to secure maximum efficiency), Kapp[3] (pre-determination of characteristic curve), Rücker[4] (limits of self-regulation), Esson,[5] (design of multipolar machines), and others. Hering,[6] Fritsche,[7] and Arnold[8] have published studies on the modes of winding armatures; and the latter has given a formula for all kinds of continuous-current machines with closed-coil armatures. Methods of analyzing the various losses of energy due to friction, hysteresis, and eddy-currents have been devised by Mordey,[9] and later by Kapp[10] and Housman,[11] independently.

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[1] *Phil. Trans.*, i. 331, 1886.

[2] *Journal de Physique* (2) ii. 240, 1887; and *Comptes Rendus*, xciii. 474, 1881.

[3] *Journ. Soc. Telegr. Engineers*, xv. 518, 1887.

[4] *Phil. Mag.* (5) xix., 462, June, 1885.

[5] *Journal Inst. Electrical Engineers*, xx. 1891.

[6] Hering's *Principles of Dynamo-electric Machines*, New York, 1889.

[7] Fritsche's *Die Gleichstrom-Dynamomaschine*, Berlin 1889.

[8] Arnold's *Die Ankerwickelung der Gleichstrom-Dynamomaschinen*, Berlin 1891.

[9] *Journal Inst. Electrical Engineers*, xviii. 620, 1889.

[10] *Electrician*, xxvi. 700, 1891.

[11] *Ib.*; see also *Journal Inst. Electrical Engineers*, xx. 303, 1891.

CHAPTER III.

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES.

ALL dynamos are based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. Faraday's principle may be enunciated as follows:—When a conductor is moved in a field of magnetic force in any way so as to cut the lines of force, there is an electromotive-force produced in the conductor, in a direction at right angles to the direction of the motion, and at right angles also to the direction of the lines of force, and to the right of the lines of force, as viewed from the point from which the motion originates.[1]

Dr. Fleming has given a most useful rule for remembering this connexion between motion, magnetism, and induced current. Hold the thumb and the first and middle fingers of the right hand as nearly as possible at right angles to each other, as in Fig. 9, so as to represent three rectangular axes in space. If the thumb point in the direction of the motion, and the forefinger point along the direction of the magnetic lines, then the middle finger will point in the direction of the induced electromotive-force.

This induced electromotive-force is, as Faraday showed, proportional to the number of lines of magnetic force[2] cut per second; and is, therefore, proportional to the intensity of the magnetic "field," and to the length and velocity of the moving conductor. For steady currents, the flow of electricity in the conductor is, by Ohm's well-known law, directly proportional to this electromotive-force, and inversely proportional to the resistance of the conductor. For sudden currents, or currents whose strength is varying rapidly, this is no longer true. And

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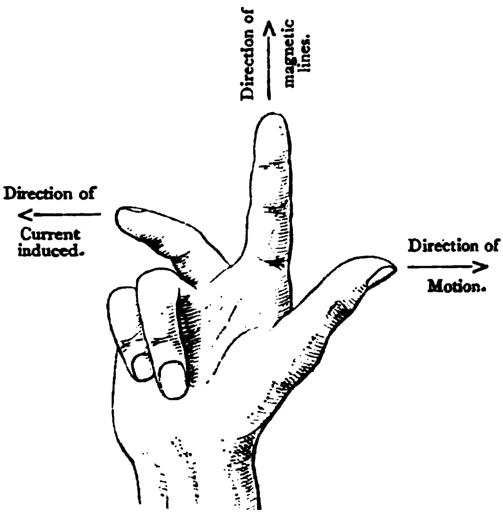
[1] A more usual rule for remembering the direction of the induced currents is the following adaptation from Ampère's well-known rule:—Supposing a figure swimming in any conductor to turn so as to look along the (positive direction of the) lines of force. Then, if he and the conductor be moved towards his right hand, he will be swimming with the current induced by this motion.

[2] For the numerical signification to be attached to the term "number of magnetic lines," see p. 123.

Fig. 9.



Right Hand.

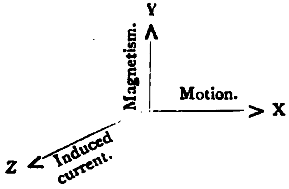


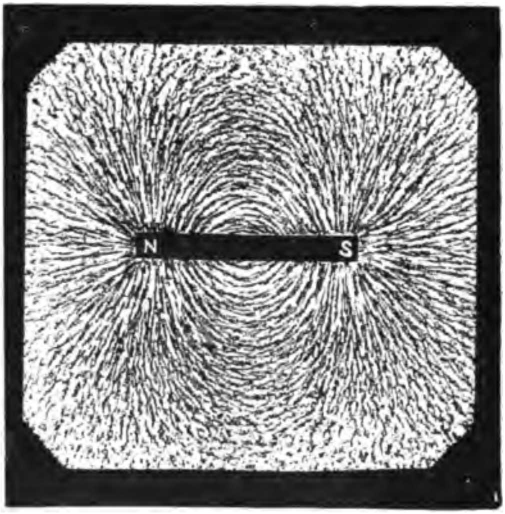
Illustration of Fleming's Rule.

it is one of the most important matters, though one too often overlooked in the construction of dynamo-electric machinery, that the "resistance" of a coil of wire, or of a circuit, is by no means the only obstacle offered to the generation of a momentary current in that coil or circuit; but that, on the contrary, the "self-induction" exercised by one part of a coil or circuit upon another part or parts of the same, is a consideration, in many cases quite as important as, and in some cases more important than, the resistance.

To understand clearly Faraday's principle—that is to say, how it is that the act of moving a wire so as to cut magnetic lines of force can generate a current of electricity in that wire—let us inquire what a current of electricity is.

A wire through which a current of electricity is flowing looks in no way different from any other wire. No man has ever yet seen the electricity running along in a wire, or knows precisely what is happening there. Indeed, it is still a disputed point which way the electricity flows, or whether or not there are two currents flowing simultaneously in opposite directions. One thing is certain; that the energy does not flow along the substance of the wire at all, but is transmitted across the surrounding medium, transversely. Until we know with absolute certainty what electricity is, we cannot expect to know precisely what a current of electricity is.

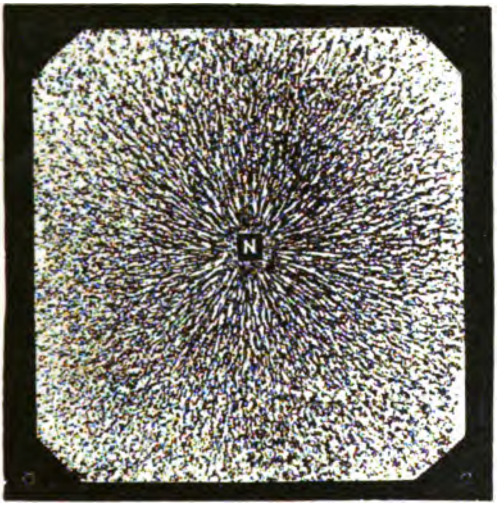
FIG. 10.



MAGNETIC FIELD OF BAR-MAGNET.

But no electrician is in any doubt as to one most vital matter, namely, that when that which is called an electric current flows through a wire, the magnetic forces with which that wire is thereby, for the time, endowed, reside not in the wire at all, but in the space surrounding it. Every one knows that the space or "field" surrounding a magnet is full of magnetic "lines of force," and that these lines run in tufts from the N-pointing pole to the S-pointing pole of the magnet, invisible until, by dusting iron filings into the field, their presence is made known, though they are always in reality there (Fig. 10). A view of the magnetic field at the pole of a bar magnet, as seen end-on, would, of course, exhibit merely radial lines, as seen in Fig. 11.

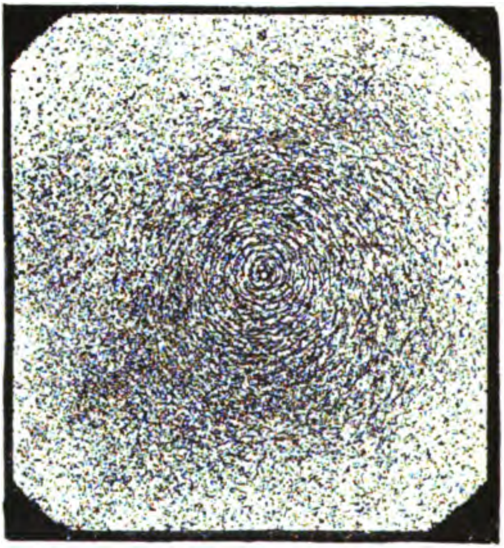
FIG. 11.



MAGNETIC FIELD ROUND ONE POLE, END-ON.

Now, every electric current (so-called) is surrounded by a magnetic field, the lines of which can be similarly revealed. To observe them, a hole is bored through a card or a piece of glass, and the wire which carries the current must be passed up through the hole. When iron filings are dusted into the field they assume the form of concentric circles (Fig. 12), showing that the lines of force run completely round the wire, and do not stand out in tufts. In fact, every conducting wire is surrounded by a sort of magnetic whirl, like that shown in Fig. 13. A great part of the energy of the so-called electric current in the wire consists in these external magnetic whirls. To set them up requires an expenditure of energy; and to maintain them requires also a constant expenditure of energy. It is these magnetic whirls which act on magnets, and cause them to set, as galvanometer needles do, at right angles to the conducting wire.

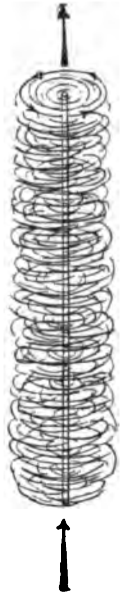
FIG. 12.



MAGNETIC FIELD SURROUNDING CURRENT. THE CONDUCTING WIRE SEEN END-ON.

Now, Faraday's principle is nothing more or less than this:—That by moving a wire near a magnet, across a space in which there are magnetic lines, the motion of the wire, as it cuts across those magnetic lines, sets up magnetic whirls round the moving wire, or, in other language, generates a so-called current of electricity in that wire. Poking a magnet pole into a loop or circuit of wire also necessarily generates a momentary current in the wire loop, because it momentarily sets up magnetic whirls. In Faraday's language, this action increases the number of magnetic lines intercepted by the circuit.

FIG. 13.

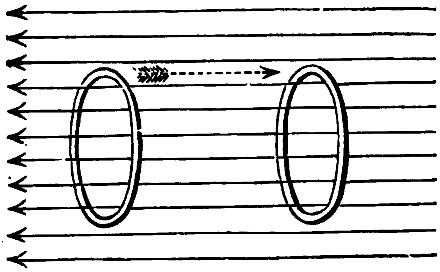


MAGNETIC WHIRL SURROUNDING WIRE CARRYING CURRENT.

It is, however, necessary that the moving conductor should, in its motion, so cut the magnetic lines as to alter the number of lines of force that pass through the circuit of which the moving conductor forms part. If a conducting circuit—a wire ring or single coil, for example—be moved along in a uniform magnetic field, as indicated in Fig. 14, so that only the same lines of force pass through it, no current will be generated. Or if, again, as in Fig. 15, the coil be moved by a motion of translation to another part of the uniform field, as many lines of force will be left behind as are gained in advancing from its first to its second position, and there will be no current generated in the coil. If the coil be merely rotated on itself round a central axis, like the rim of a fly-wheel, it will not cut any more lines of force than before, and this motion will generate no current. But if, as in Fig. 16, the coil be tilted in its motion across the uniform field, or rotated round any axis in its own plane, then the number of lines of force that traverse it will be altered, and currents will be generated. These currents will flow round the ring coil in the right-handed direction (as viewed by a person looking along the magnetic field in the direction in which the magnetic lines run), if the effect of the movement is to diminish the number of lines of force that cross the coil; they will flow round in the opposite sense, if the effect of the movement is to increase the number of intercepted lines of force.

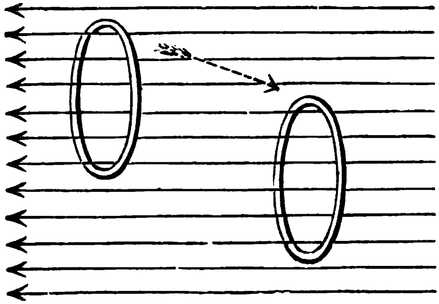
If the field of force be not a uniform one, then the effect of taking the coil by a simple motion of translation from a place where the lines of force are dense to a place where they are less dense, as from position 1 to position 2 in Fig. 17, will be to generate currents. Or, if the motion be to a place where the lines of force run in the reverse direction,[1] the effect will be the same, but even more powerful.

FIG. 14.



CIRCUIT MOVED WITHOUT CUTTING LINES OF FORCE OF UNIFORM MAGNETIC FIELD.

FIG. 15.



CIRCUIT MOVED WITHOUT CUTTING ANY MORE LINES OF FORCE.

We may now summarise the points under consideration and some of their immediate consequences, in the following manner :—

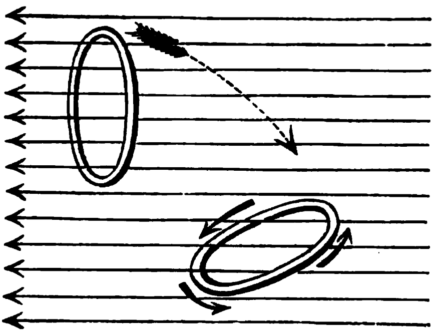
(1.) A part, at least, of the energy of an electric current exists in the form of magnetic whirls in the space surrounding the conductor.

---

[1] As a matter of fact, it would be impossible to have a magnetic field exactly like Fig. 11; for in the intermediate part, between the upper and lower fields, the magnetic lines would be of curved complex form.

(2.) Currents can be generated in conductors by setting up magnetic whirls round them.

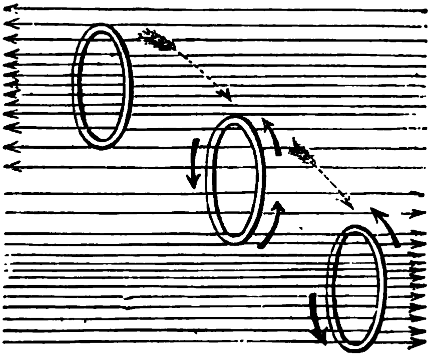
FIG. 16.



CIRCUIT MOVED SO AS TO ALTER NUMBER OF LINES OF FORCE THROUGH IT.

(3.) We can set up magnetic whirls in conductors by moving magnets near them, or moving them near magnets.

FIG. 17.



MOTION OF CIRCUIT IN NON-UNIFORM MAGNETIC FIELD.

(4.) To set up such magnetic whirls, and to maintain them by means of an electric current circulating in a coil, requires a continuous expenditure of energy, or, in other words, consumes power.

(5.) To induce currents in a conductor, there must be relative motion between conductor and magnet, of such a kind as to alter the number of lines of force embraced in the circuit.

(6.) Increase in the number of lines of force embraced by the circuit produces a current in the opposite sense to decrease.

(7.) Approach induces an electromotive-force in the opposite direction to that induced by recession.

(8.) The more powerful the magnet-pole or magnetic field the higher will be the electromotive-force generated.

(9.) The more rapid the motion, the higher will be the electromotive-force.

(10.) By joining in series a number of such moving conductors, the electromotive-forces in the separate parts are added together; hence very high electromotive-forces can be obtained by using numerous coils properly connected.

(11.) Since the quantity or strength of the current depends on the resistance of the conductors in the circuit, as well as on the electromotive-force, all unnecessary resistance should be avoided.

(12.) Approach being a finite process, the method of approach and recession (of a coil towards and from a magnet pole) must necessarily yield currents alternating in direction.

(13.) By using a suitable commutator, all the currents, direct or inverse, produced during recession or approach, can be turned into the same direction in the wire that goes to supply currents to the external circuits; and if the rotating coils are properly grouped so that before the electromotive-force in one set has died down another set is coming into action, then it will be possible, by using an appropriate commutator, to combine their separate currents into one practically uniform current.

(14.) To the moving conductor which is generating the electromotive-force by cutting the magnetic lines, it makes no difference what the origin of those lines is, whether from a permanent magnet of steel or from an electromagnet, provided the number of magnetic lines so cut is the same.

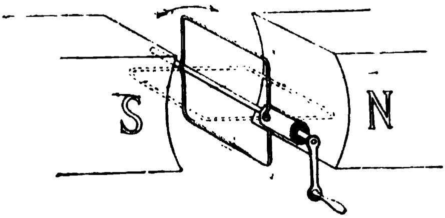
(15.) To the moving conductor it makes no difference what the origin of the motion is. Whether the motion be due to a steam-engine, or to a gas-engine, or to hand-driving, or to the driving of an electric current in the wire itself (as in the case of electric motors), it makes no difference to the moving conductor, which, provided the speed and the number of magnetic lines to be cut are given, will generate the same electromotive-force.

To make more clear the considerations which will occupy us when discussing individual types of dynamo, we will first examine some fundamental points in the general mechanism and design of dynamo machines; for there are many additional conditions to be observed in the construction of a successful dynamo. We will deal with the various matters in order, beginning with the various organs or parts of the machine. Having discussed these, we take up the nature of the processes that go on in the machine when it is at work, the action of the magnetic field on the rotating armature, the reactions of the armature upon the field in which it rotates. We must then enter upon the magnetic part of the subject, and discuss the magnetic properties of iron so far as is needed for the purpose of dynamo design. We shall then consider the design of field-magnets, and the design and construction of armatures.

ORGANS OF DYNAMO-ELECTRIC MACHINES.

The simplest conceivable dynamo is that sketched in Fig. 18, consisting of a single rectangular loop of wire rotating in a simple and uniform magnetic field between the poles of a large magnet. If the loop be placed at first in the vertical plane, the number of lines that pass through it from right to left will be a maximum, and as it is turned into the horizontal position the number diminishes to zero; but on continuing the rotation the lines begin again to thread through the loop from the opposite side, so that there is a negative maximum when the loop has been turned through 180°. During the half-revolution, therefore, currents will have been induced in the loop, and these currents will be in the direction from back to front in the part of the loop which is rising on the left, and in the opposite direction, namely from front to back, in that part which is descending on the right. On passing the 180° position, there will begin an induction in the reverse sense, for now the number of negative lines of force is diminishing, which is equivalent to a positive increase in the number of lines of force: and this increase would go on until the loop reached its original position, having made one complete turn. If, then, to each end of the loop there were separately attached a metal collar on the shaft, and on each collar there pressed a spring, wires connected to these springs would convey an ***alternating current*** to the circuit. If, however, it is desired to adapt the apparatus to furnish a continuous current, a special adjunct must be added.

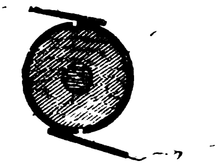
Fig. 18.



Ideal Simple Dynamo.

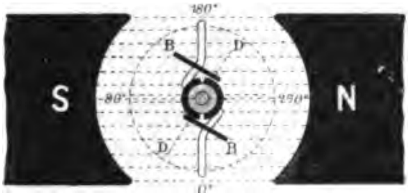
To commute these alternately-directed currents into one direction in the external circuit, there must be applied a commutator consisting of a metal tube slit into two parts, and mounted on a cylinder of hard wood or other suitable insulating material; each half being connected to one end of the loop, as indicated in Fig. 18. Against this commutator press a couple of metallic springs or "brushes" (Fig. 19), which lead away the currents to the main circuit. It is obvious that if the brushes are so set that the one part of the split tube slides out of contact, and the other part slides into contact with the brush, at the moment when the loop passes through the positions when the induction reverses itself, the alternate currents induced in the loop will be "commuted" into one direction through the circuit. We should expect therefore the brushes to be set so that the commutation shall take place exactly as the loop passes through the vertical position. In practice, however, it is found that a slight forward lead must be given to the brushes, for reasons which will presently appear. In Fig. 20 are shown the brushes B B′, displaced so as to touch the commutator not exactly at the highest and lowest points, but at points displaced in the direction of the line D D′ which is called the "diameter of commutation." The argument is in no wise changed if for the single ideal loop we substitute, as proposed by Sturgeon in 1835, the simple rectangular coil represented in Fig. 21, consisting of many turns of wire, in each of which a simultaneous inductive action is going on, making the total induced electromotive-force proportionally greater. This form, with the addition of an iron core is, indeed, the form given to armatures in 1856 by Siemens, whose shuttle-wound armature is represented in section in Fig. 22. A small magneto-electric machine of the old pattern, having the shuttle-wound armature, is shown in

FIG. 19.



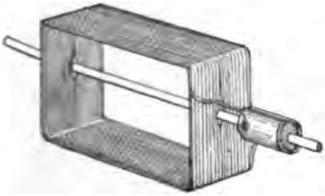
TWO-PART COMMUTATOR.

FIG. 20.



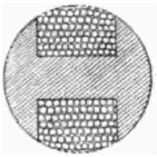
SIMPLE LOOP IN SIMPLE FIELD.

FIG. 21.



SIMPLE RECTANGULAR COIL.

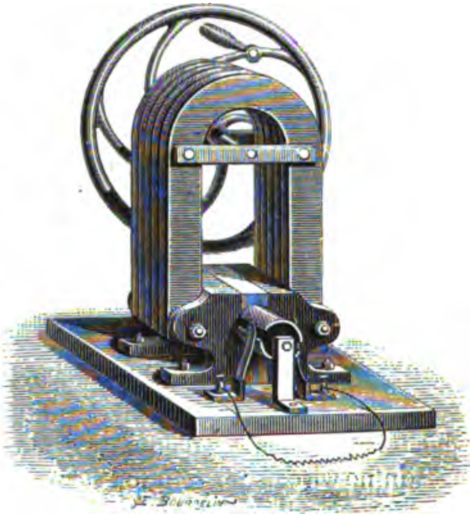
FIG. 22.



SECTION OF OLD SHUTTLE-WOUND SIEMENS ARMATURE.

Fig. 23. Though this form has now for many years been abandoned, save for small motors and similar work, it gave a

FIG. 23.



OLD SIEMENS MACHINE, WITH SHUTTLE-WOUND ARMATURE AND PERMANENT MAGNETS.

great impetus to the machines of its day; but for all large work it has been entirely superseded by the ring armatures and drum armatures presently to be described.

ESSENTIAL PARTS OF A DYNAMO.

We have seen that the dynamo in its simplest form consists of two main portions: (1) an *armature*, which in revolving induces electromotive-forces in the copper conductor wound upon it; (2) a *field-magnet*, that is to say a magnet whose function is to provide a field of magnetic lines, to be cut by the armature conductors as they revolve. In all dynamos, whether for continuous currents or for alternate currents, these two parts can be recognized. In almost all continuous-current machines the field-magnet stands still, and consists of a comparatively simple and massive electromagnet; whilst the armature, which is a more complex structure, is the portion which rotates. In alternate-current machines the field-magnet is usually multipolar, and in the majority of cases is stationary, whilst the armature rotates; nevertheless there are many alternators of recent pattern in which the armature stands still and the field-magnet rotates. The criterion as to which portion is properly called "field-magnet," and which "armature," is not the question of rotation or otherwise. The name of field-magnet is properly given to that part which, whether stationary or revolving, maintains its magnetism steady during the revolution; and the name armature is properly given to that part which, whether revolving or fixed, has its magnetism changed in a regularly repeated fashion when the machine is in motion.

In the case of continuous-current machines there is another feature of first importance, namely, the apparatus for collecting the currents from the revolving armature. This apparatus consists of two essential parts; the *commutator* (or *collector*) attached to the armature and revolving with it, and the *brushes*. The latter, which are conducting contact pieces held pressed against the surface of the rotating commutator, are provided with special *brush-holders* mounted upon an adjustable frame or *rocker*.

In the case of alternate-current machines there is no need of a commutator; but, in general, these machines have to be provided with some device for making a sliding connexion. For in those forms in which the armature rotates, its coils must be brought into continuous metallic relation with the conductors of the main circuit; and in those forms in which the armature is stationary and no such arrangement is needed at that part, there must still be sliding contacts to maintain the coils of the revolving field-magnet part in continuous metallic connexion with the auxiliary exciting circuit. In either case the appropriate device consists of a pair of *collecting rings*, against each of which a *brush* presses.

In addition to the electrical and magnetic features enumerated above, there are certain purely mechanical features which need to be considered. The revolving part must be mounted on an appropriate *spindle* or *shaft*, the design of which is a matter of mechanical engineering. To transmit the power from the spindle to the revolving conductors of the armature there are required *driving attachments* properly secured to the spindle. The spindle itself must be supported in suitable *bearings*, and be provided with *lubricators* to secure cool running. To receive the power from the engine a *pulley* must be provided, unless the dynamo is to be driven direct by a *coupling* from an engine mounted on the same bed-plate. Lastly, the whole dynamo must be erected upon an appropriate *bed-plate*, which in some cases is placed upon *rails*, so that it may be shifted from time to time by the aid of tightening screws, as the belt grows slack.

In the considerations which follow, attention will be concentrated upon dynamos for producing continuous currents, the various organs of which will be duly considered. The design of alternate-current machines will be discussed in a later chapter.

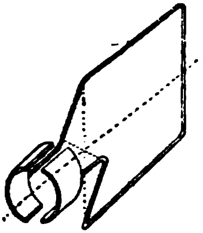
CONTINUOUS-CURRENT DYNAMOS.

Armatures.

Returning to the ideal simple loop, we may exhibit it in its relation to the 2-part commutator somewhat more clearly by referring to Fig. 24. The same split-tube or 2-part commutator will suffice if a loop of two or more turns be substituted, as shown in Fig. 25, for the single turn.

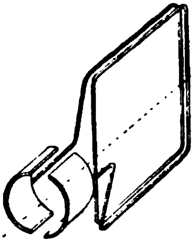
But we may substitute also for the one loop a small coil consisting of several turns wound upon an iron ring. This coil (Fig. 26), which may be considered as one section of a Pacinotti or Gramme ring, will have lines of force induced through it as the loop had. In the position drawn, it occupies the highest point of its path, and the induction of lines of force through it will be a maximum. As it turns, the number of lines of force threaded through it will diminish, and become zero when it is at 90° from its original position. But a little consideration of its action will suffice to show that if another coil be placed at the opposite side of the ring it will be undergoing exactly similar inductive action at the same moment, and may therefore be connected to the same commutator. If these two coils are united in parallel arc, as shown in Fig. 27, the joint electromotive-force will be the same as that due to either separately; but the resistance offered to the current by the two jointly is half that of either. It is evident that we may connect two parallel loops in a similar fashion to one simple 2-part collector. If the two loops are of one turn each, we shall have the arrangement sketched in Fig. 28; but the method of connecting is equally good for loops consisting of many turns each.

FIG. 24.



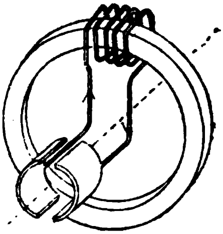
SIMPLE LOOP ARMATURE.

FIG. 25.



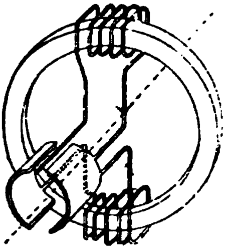
LOOP ARMATURE OF TWO TURNS.

FIG. 26.



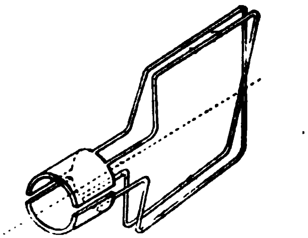
SIMPLE RING ARMATURE WITH ONE COIL.

FIG. 27.



SIMPLE RING ARMATURE WITH TWO COILS IN PARALLEL.

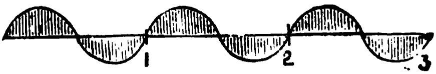
FIG. 28.



SIMPLE LOOP ARMATURE WITH TWO COILS IN PARALLEL.

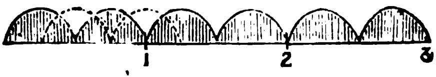
Now, with all these arrangements involving the use of a 2-part commutator, whether there be one circuit only or two circuits in parallel in the coils attached thereto, there is the disadvantage that the currents, though commutated into one direction, are not absolutely continuous. In any single coil without a commutator there would be generated, in successive revolutions, currents whose variations might, if the coil were destitute of self-induction, be graphically expressed by a recurring sinusoidal curve, such as Fig. 29. But if by the addition of a simple split-tube commutator the alternate halves of these currents are reversed, so as to rectify their direction through the rest of the circuit, the resultant currents will not be continuous, but will be of one sign only, as shown in Fig. 30, there being two currents generated during each revolution of the coil. The currents are now "rectified," or "redressed," as our continental neighbours say, but are not continuous. To give *continuity* to the currents, we must advance from the simple 2-part commutator to a form having a larger number of parts, and employ therewith a larger number of coils. The coils must also be so arranged that one set comes into action while the other is going out of action. Accordingly, if we fix upon our iron ring two sets of coils at right angles to each other's planes, as in Fig. 31, so that one comes into the position of best action while the other is in the position of least action (one being parallel to the lines of force when the other is normal to them), and their actions be superposed, the result will be, as shown in Fig. 32, to give a current

FIG. 29.



SIMPLE CURVE OF SINES, REPRESENTING AN ALTERNATING OR UNDULATORY CURRENT.

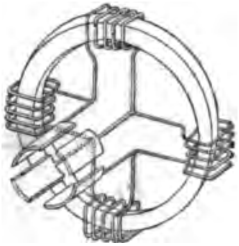
FIG. 30.



CURVE OF RECTIFIED OR COMMUTED ALTERNATING CURRENT.

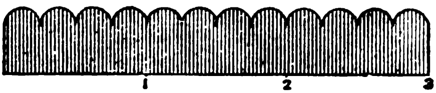
which is continuous, but not steady, having four slight undulations per revolution. If any larger number of separate coils are used, and their effects, occurring at regular intervals, be superposed, a similar curve will be obtained, but with summits proportionately more numerous and less elevated. When the number of coils used is very great, and the overlappings of the curves are still more complete, the row of summits will form practically a straight line, or the whole current will be practically constant. As arranged in Fig. 31, the four coils are all united together in a *closed* circuit, the end of the first being united to the beginning of the second, and so forth all round, the last section closing in to the first. For perfect uniformity of effect, the coils on the armature ought to be divided into a very large number of sections (see calculations p. 221, Chap. IX.), which come in regular succession into the position of maximum induction at regular intervals one after the other. In Fig. 33 a sketch is given of a drum armature wound with two pairs of coils at right angles one to the other, and connected to a 4-part commutator. A little examination of Figs. 31 and 33 will show that each section of the coils is connected to the next in order to it; the whole of the windings constituting, therefore, a single closed coil. Also, the end of one section and the beginning of the next are both connected with a segment of the commutator. In practice, the commutator segments are not mere slices of metal tubing, but are built up of a number of parallel bars of copper, gun-metal, or

FIG. 31.



FOUR-PART RING ARMATURE (CLOSED COIL).

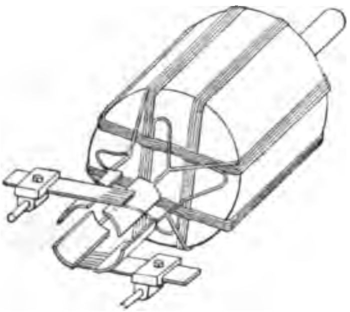
FIG. 32.



CURVE OF CONTINUOUS BUT NON-UNIFORM CURRENT.

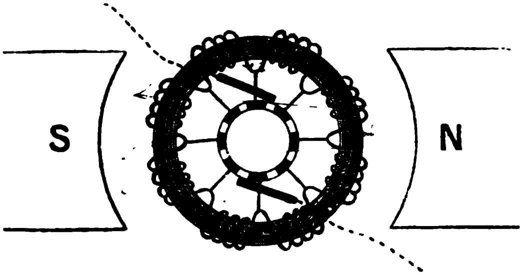
phosphor-bronze, such as may be seen in Fig. 36, p. 43, placed round the periphery of a cylinder of some insulating substance. It will also be noticed that, owing to the fact that there is a continuous circuit all round, there are two ways in which the current may flow through the armature from one brush to the other, as in all the ring and drum armatures; of which, indeed, Figs. 31 and 33 may be taken as simplified instances. The same reasoning now applied to 4-part armatures holds good for those having a still larger number of parts, such as is shown in Fig. 34. Of these more will be said in the subsequent chapters. Let it suffice to say here that in closed-coil armatures, whether of the "ring" or the "drum" type, there are usually as many segments to the commutator as there are *sections* or groups of coils in the circuit of the armature. The special case of *open-coil armatures* is considered in Chapter XVII., p. 449. In these machines the separate coils are not connected up together in series, and a special form of commutator is used instead of the usual arrangement of a large number of parallel bars.

FIG. 33.



FOUR-PART DRUM ARMATURE (CLOSED COIL).

FIG. 34.



SIMPLE RING ARMATURE, SHOWING CONNEXIONS OF CLOSED COIL.

As already explained, the "brushes" press against the commutator, being usually held in position by a spring. As the commutator rotates, each of the bars passes successively under the brush, and makes contact with it. At one side—that towards which the two currents in the armature are flowing—the current flows from the commutator-bar into the brush. At the other side the return current flows from the negative brush into the commutator-bar in contact with it, and thence divides into two parts in the two circuits of the armature. Since the brushes press against the commutator-bars, then when one commutator-bar is leaving and the next coming up into contact with the brush, there will be contact made for a moment with two adjacent bars; and the coil, or section, whose two ends are united to these two bars, will, for an instant, be short-circuited. The effect of this will be considered in dealing with the reactions in armatures at a later stage.

So far, the only types of armature considered have been the "drum" type, and the "ring" type; but these are not the only possible cases. The object of all such combinations of coils is to obtain the practical continuity and equability of current explained above. To attain this end it is needful that some of the individual coils should be moving through the position of maximum action, whilst others are passing through the neutral point, and are temporarily idle. Hence, a symmetrical arrangement of the individual coils or groups of coils around an axis is needed; and such symmetrical arrangements may take one of the four following types:—

(1) *Ring armatures*, in which the coils are grouped upon a ring whose principal axis of symmetry is its axis of rotation also.

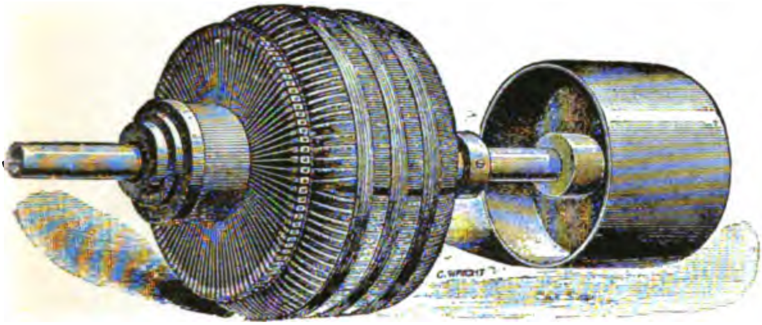
(2) *Drum armatures*, in which the coils are wound longitudinally over the surface of a drum or cylinder.

(3) *Pole armatures*, having coils wound on separate poles projecting radially all round the periphery of a disk or central hub.

(4) *Disk armatures*, in which the coils are flattened against a disk.

Ring armatures are found in many machines, but the ingenuity of inventors has been exercised chiefly in three directions :—The securing of practical continuity, the avoidance of eddy-currents in the cores, and the reduction of useless resistance. In the greater part of these machines the armatures are constructed with closed coils ; but there is no reason why open-coil armatures should not be constructed in the ring form, as indeed is the case with the well-known Brush arc-light dynamo. Most inventors have been content to secure approximate continuity by making the number of sections numerous. Pacinotti's early dynamo had the coils wound between projecting teeth upon an iron ring. Gramme rejected these cogs, preferring that the coils should be wound round the entire surface of the endless core. To prevent wasteful currents in the cores, Gramme employed for that portion a coil of varnished iron wire of many turns. For cylindrical armatures flat core-disks of sheet iron are now almost universally preferred. For discoidal ring armatures the core is built of hoops. The parts of the copper coils which pass through the interior of the ring are inoperative in cutting magnetic lines, unless there are pole-pieces of the field-magnet projecting internally. Hence, in the ordinary forms of dynamo with exterior magnets, the inner parts of the ring winding act merely as conductors and not as inductors, and offer a certain amount of wasteful resistance. But this resistance in well-designed machines is insignificant compared with that of the external circuit, and the disadvantage is largely imaginary. Inventors have essayed to reduce the amount of copper, by either fitting projecting flanges to the pole-pieces, or by using internal magnets, or else by flattening the ring into a disk form, so as to reduce the interior parts of the ring coils into an insignificant amount. Indeed, the flat-ring armatures may be said to present a distinct type from those in which the ring tends to the cylindrical form. In some large recent German dynamos the ring is outside the field-magnets, so that the outer part of the windings are non-inductive or idle ; and the currents are collected direct from the ring by brushes which trail on its periphery. The various modes of winding and connecting up the conductors on an armature are specially considered in Chapter XII. A finished ring armature with its commutator and driving pulley is shown in Fig. 35.

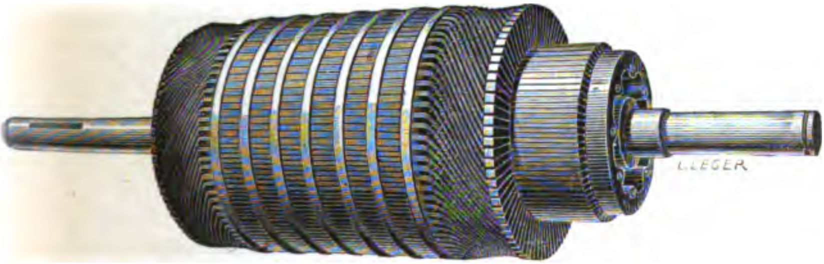
FIG. 35.



RING ARMATURE OF GRAMME DYNAMO (FULLER'S PATTERN).

Drum armatures, as first constructed by Siemens, had iron cores made of wire wound upon an internal non-magnetic nucleus. Weston substituted stamped core-disks of iron with teeth. Edison, iron core-disks without teeth. Special modes of winding or joining the copper conductors have been devised by many inventors. A complete drum armature is depicted in Fig. 36, which shows the overlapping of the windings at the end of the drum, the connexions to the commutator, and the external binding wires that keep the coils from flying out.

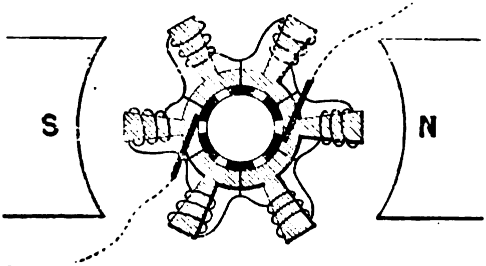
FIG. 36.



DRUM ARMATURE (ALLGEMEINE CO.'S PATTERN).

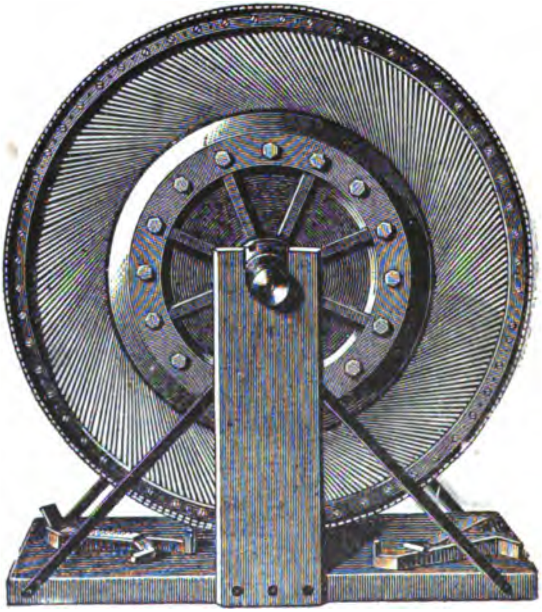
Pole armatures, having the coils wound upon radially projecting poles have been devised by Allan, Lontin, and Weston. The principle of Lontin's machine, in which the coils

FIG. 37.



SIMPLE POLE ARMATURE SHOWING CONNEXIONS.

FIG. 38.



DISK ARMATURE OF FRITSCHE MACHINE.

are connected like the sections of a Pacinotti or Gramme ring, is indicated in Fig. 37. Here the diameter of commutation is parallel to the polar diameter, because the number of lines of force in this case is a maximum in the coils that are on the right and left positions. This armature is structurally a difficult one, because it is not mechanically strong unless the cores are solid; and solid cores are electrically bad owing to their heating. It is impracticable, too, in this form to have very many sections, and the coils act, by reason of their position, prejudicially on one another. This form of armature is obsolete for direct-current machines.

Disk armatures are now differentiated into two kinds: (1) those in which the coils are grouped on a number of small bobbins, side by side, an arrangement suitable for alternate current machines, such as those of Wilde, Siemens, Ferranti, and Mordey; (2) those in which the windings are made to overlap over a considerable angle of the periphery, as in the disk dynamos of Pacinotti, of Rupp and Jehl, of Desroziers, and of Fritsche, all of which are adapted to give continuous currents. It is usual, in the disk form of armature, to dispense with any iron core, for, the armature being thin, can be inserted in a comparatively narrow gap between the polar surfaces of the field-magnet. A finished disk armature is shown in Fig. 38, belonging to a Fritsche machine; the commutator being on the outside of the disk.

Armature Cores.

Whenever iron is employed in armatures, it must be slit or laminated, so as to prevent the generation of eddy-currents. Such iron cores should be structurally divided in planes normal to the circuits round which electromotive-force is induced; or should be divided in planes parallel to the lines of force and to the direction of the motion. Thus, drum armature cores should be built of discs of thin sheet iron. Ring armatures, if of the cylindrical or elongated type, should have cores made up of rings stamped out of sheet iron and clamped together side by side; but if of the flat ring type they should be built of concentric hoops. Cores built up of varnished iron wire, or of thin disks of sheet iron separated by varnish, asbestos paper, or mica, partially realise the required condition. The magnetic discontinuity of wire cores is, however, to a certain extent disadvantageous; it is better that the iron should be without discontinuity in the direction in which it is to be magnetized. It should, therefore, be laminated into sheets, rather than subdivided into wires. Pole armatures are structurally unsatisfactory unless the projections which receive the coils are very short. Cores of solid iron are quite inadmissible, as currents are generated in them and heat them. Cores of solid metal other than iron—for example, of gun-metal, or of phosphor-bronze—should on no account be used in any armature; but the driving supports are necessarily strong and solidly made.

Fundamental Points in Design.

As has already been pointed out, the function of the field-magnet is to provide a large number of magnetic lines, whilst the function of the armature is to cut the magnetic lines so provided. The iron core inside the armature may be regarded, therefore, as belonging to the magnetic circuit of the field-magnet; the true armature consisting of the rotating copper conductors. There is no electrical necessity for the iron core inside the armature to rotate; indeed, in some ways it would act more efficiently if it did not. But purely mechanical considerations require that in both ring armatures and drum armatures the core should rotate with the coils. In all dynamos the electromotive-force is proportional at every instant to the rate at which the magnetic lines are being cut, and this will again be proportional to three quantities: (1) the number of magnetic lines provided by the field-magnet, (2) the number of copper conductors connected together upon the armature, (3) the speed at which these conductors are driven. In alternate-current dynamos the rate of cutting is continually changing in a regular periodicity; in continuous-current machines the rate of cutting is automatically averaged and made steady by the method of grouping the conductors around the ring or drum in a closed circuit, and connecting to the commutator. It is shown later, on p. 211, that, for continuous-current dynamos of the common two-pole type, the electromotive-force generated in the revolving armature may be calculated as follows :—

Let the speed of the armature, or revolutions *per second* be called n.

Let the number of conductors that are joined in series with one another around the armature be called C.

Let the number of magnetic lines which pass through the armature core from side to side be called N.

Let the number of volts of electromotive-force generated by the rotating armature be called E.

Then the following formula holds good :—

$$E = n \times C \times N \div 100{,}000{,}000.$$

Example.—In a Kapp dynamo used at the Technical College, Finsbury, C = 120 ; N = 7,170,000 ; at a speed of 780 revs. per min., or 13 revs. per sec., the whole electromotive-force generated is 111 volts.

From the above formula it will be seen that the electromotive-force at which any dynamo is to deliver its current is the product of three factors ; and it can be increased by increasing any one of the three, or all of them. In a given machine C is a constant, and N, the magnetic flux, cannot be increased beyond the capacity of the iron core to carry magnetic lines. But if it is desired to design a new machine, obviously any value might be assigned to any of the three factors, provided the product came to the required amount. It is, therefore, a question of expediency whether in so designing a machine we will increase any one of the factors rather than any other. To increase N means using a larger cross section of iron, and a correspondingly big field-magnet, and therefore involves additional cost of iron. To increase C means increasing the weight, and therefore the cost of the copper conductors, for the section of these depends on the current they have to carry, whilst the electromotive-force generated depends on their number, and on the rate at which they cut the magnetic lines. Moreover, experience shows that in thus increasing the quantity of copper upon an armature core of given size involves, when once a certain limit is reached, the very serious difficulty that the machine cannot be run without sparking at its brushes. To increase the speed n involves mechanical difficulties about lubrication and liability of the parts to fly out; in fact, mechanical considerations limit the speed. For many years modern practice has gone in the direction of keeping the speed slow, and in keeping down the relative amount of copper, the quantity of iron being relatively large; for not only so is the total cost of the machine less than it would be if the relative amounts of copper and iron were reversed, but the expense and trouble of maintenance is found to be less. Machines with a relatively massive and powerful field-magnet spark less, and require less attention to regulation and need fewer renewals of the brushes and commutator than do those which have a comparatively weak field-magnet. Of late there has been some tendency, however, to a movement in the opposite direction, because if, by special designing, without sacrificing the advantages attained in the possession of a relatively powerful field-magnet, the speed and the weight of copper on the armature can be increased; the output of such a machine will be proportionally augmented at a small increase of total weight and total prime cost.

For alternate-current machines the fundamental formula requires to be completed by the introduction of two additional factors. Such machines are usually multipolar, and if N represents the magnetic flux around any one of the individual magnetic circuits, the total magnetic effect must be increased by multiplying by the number p of pairs of magnetic poles that surround the armature. Further, a constant k must be inserted, the numerical value of which (varying from 1·8 to 2·5 in actual machines) depends on the relative breadths of the coils and pole-pieces employed. The general formula for the volts generated in any alternate-current machine will then be:—

$$\mathrm{E} = k \times p \times n \times \mathrm{C} \times \mathrm{N} \div 100{,}000{,}000.$$

Example.—In one of Kapp's alternators, $k = 2{\cdot}3$; $p = 6$; $\mathrm{C} = 1190$; $\mathrm{N} = 1{,}250{,}000$, when running at 700 revs. per min.; so that $n = 11{\cdot}6$, $\mathrm{E} = 2360$.

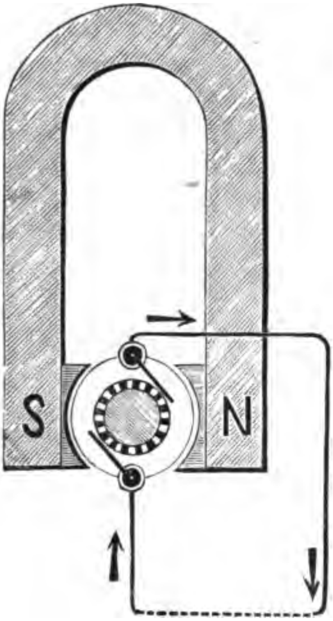
METHODS OF EXCITING THE FIELD-MAGNETISM.

The five simple methods of exciting the magnetism that is to be utilized in the magnetic field may be grouped under two heads, according to whether the armature of the machine supplies the machine's own magnetism or whether the magnetism is provided for from some other source.

Magneto-dynamo.—In the oldest machines there was no attempt to make the machine excite its own magnetism, which was provided for it once for all by the employment of a permanent magnet of steel. Unfortunately, the supposed permanent magnetism of steel magnets slowly decays, and is diminished by every mechanical shock or vibration to which the machine is subjected.

The *magneto-electric machine*, or *magneto-dynamo*, a diagrammatic drawing of which is given in Fig. 39, survives, indeed, in numerous small types of machines. It has the serious disadvantage of being both heavier and bulkier than other dynamos of equal capacity, because steel cannot be permanently magnetized to the same high degree as that to which wrought iron, or cast iron, or even steel itself, can be temporarily raised.

FIG. 39.

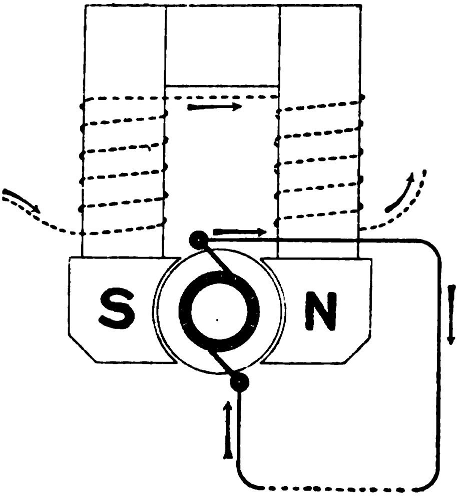


THE MAGNETO-DYNAMO.

Separately-excited Dynamo.—It was an obvious step to substitute for steel magnets, electromagnets excited by means of currents from some independent source such as a voltaic battery. The *separately-excited dynamo* (Fig. 40) comes therefore second in the order of development. Though used by

Faraday, this method did not come into acceptance until, in 1866, Wilde employed a small auxiliary magneto machine to furnish currents to excite the field-magnets of a larger dynamo. The separately-excited dynamo, in common with the magneto machine, possesses the property that, saving for reactions due to the armature current, the magnetism in its field, and therefore the electromotive-force of the machine, is independent of changes of resistance going on in the working circuit.

FIG. 40.



THE SEPARATELY-EXCITED DYNAMO.

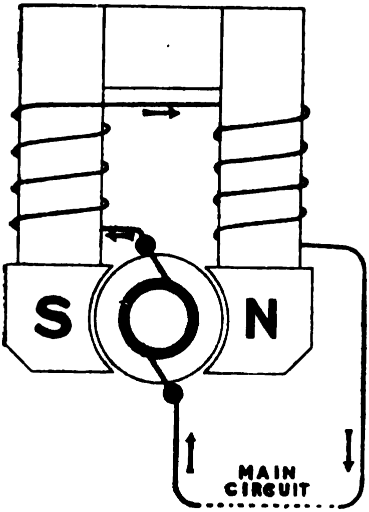
The dynamos of either of the preceding kinds can be governed, either by altering the speed or by altering the amount of magnetism that passes across the armature. For long it has been the fashion to control the electromotive-force of magneto machines by the device of providing a movable piece of iron, which could be placed more or less over the poles of the field-magnet, serving as a magnetic shunt to divert some of the magnetism from the armature. In the case of separately-excited machines there are two other methods of diminishing at will the effective magnetism, namely by weakening the exciting current, for example, by introducing more or less resistance into the exciting circuit, or by altering the number of turns of wire through which the existing current circulates around the field-magnet.

The simple methods of making dynamos self-exciting are three in number: (1) the whole current from the armature may be carried through field-magnet coils that are connected in series with the main circuit; (2) a portion of the current from the armature may be diverted from the main circuit and carried through field-magnet coils of somewhat high resistance connected as a shunt; (3) the current required to excite the field-magnet may be procured either from a second armature revolving in the same field, or (if the armature consists of many coils) from some of the coils of the armature that may be separately joined up for that purpose.

Series Dynamo.—The series-wound, or ordinary dynamo (Fig. 41), possesses but one circuit. It has the disadvantage of not starting action until a certain speed has been attained, or, unless the resistance of the circuit is below a certain limit; the machine refusing to magnetize its own magnets when there is too much resistance and too little speed. The least speed of self-excitation is a measure of the goodness of the magnetic circuit. Series-wound machines are also liable to become reversed in polarity, a serious disadvantage, and one that unfits this type of machine for employment in electroplating or for charging accumulators. Any increase in the resistance of the series-wound dynamo lessens its power to supply current, because it diminishes the current in the coils of the field-magnet, and therefore diminishes the amount of the effective magnetism. When lamps are in series (as is usual in an arc-light circuit) in the circuit of a series-wound dynamo, the switching on of an additional lamp both adds to the resistance of the circuit and diminishes the power of the machine to supply current. On the other hand, when lamps are in parallel across a pair of mains fed by a dynamo, if that dynamo is series-wound, the switching on of additional lamps not only diminishes the resistance of the circuit, but causes the field-magnets to be further excited by the increased current, so that the more lamps are on, the greater becomes the risk of their getting too great a current.

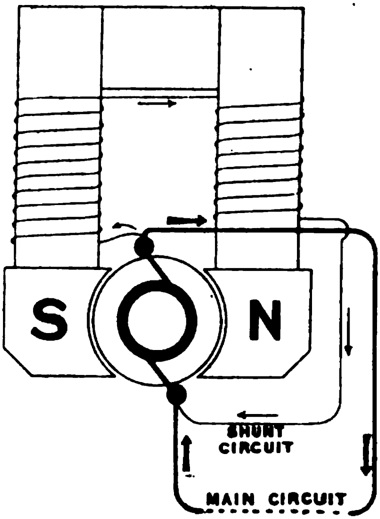
Shunt Dynamo.—In the shunt-wound machine (Fig. 42) the field-magnet is wound with many turns of fine wire, to receive only a small portion of the whole current generated in the armature. These coils are connected to the brushes of the machine, and constitute a by-pass circuit or shunt. Shunt machines are less liable to reverse their polarity than series machines. Owing to the somewhat greater cost of the fine wire of the shunt-coil, they are slightly dearer in prime cost than series machines of equal power, but the expenditure of electric energy to keep up the magnetism is practically alike in both cases. It requires the same expenditure of electric energy to magnetize an electromagnet to the same degree, whether the coil consists of many turns of thin wire or of a few turns of thick wire, provided the *volume* occupied by the coil be alike in the two cases, and provided the

FIG. 41.



THE SERIES DYNAMO.

FIG. 42.



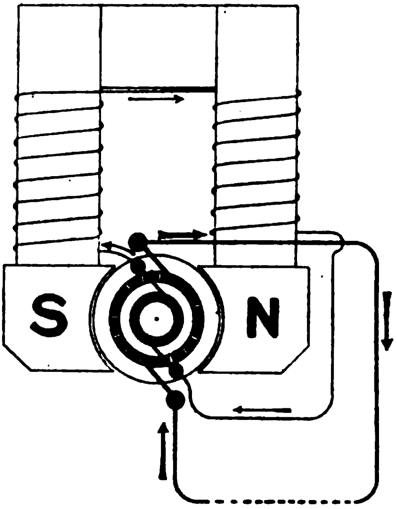
THE SHUNT DYNAMO.

insulation is relatively of the same thickness. When a shunt machine is supplying lamps in parallel, the addition of lamps which brings down the nett resistance of the circuit will increase the current, but not proportionally, for when the resistance of the main circuit is lowered, a little less current goes round the shunt and the magnetism drops a trifle; nevertheless, such a machine may regulate itself tolerably well if the internal resistance of its armature is very small. For a set of lamps in series, the power of a shunt dynamo to supply the needful current increases with the demands of the circuit, since any added resistance sends additional current round the shunt in which the field-magnets are placed, and so makes the magnetic field more intense. On the other hand, there is a greater sensitiveness to inequalities of driving, in consequence of the great self-induction in the shunt; and for machines giving high voltage shunt winding is too costly. The shunt part of the circuit in the present case consists of a fine wire of many turns wound upon iron cores. It therefore has a much higher coefficient of self-induction than the rest of the circuit; and, consequently, any sudden variations in the speed of driving cannot but affect the current in the main circuit more than in the shunt. Briefly, the shunt winding, though it steadies the current against perturbations due to changes of resistance in the circuit, does not steady the current against perturbations due to changes in speed of driving. The electromotive-force of the shunt machine can be controlled by introducing a variable resistance into the shunt circuit.

A variety of the shunt method involves the use of a *third brush*, placed against the commutator at some point intermediate between the points of highest and lowest potential. The ends of the exciting coil are connected to the third brush and to one of the ordinary brushes, so that the exciting coil receives a fraction of the volts generated in the armature.

Separate-circuit Self-exciting Dynamo.—There is yet the third species (Fig. 43) of self-exciting machine, in which the field-magnet coils are arranged to form part of a circuit entirely separate from the main circuit, but are supplied with currents from coils rotating in the field. There are two ways of carrying this into effect: (1) a second armature may be made to rotate between the same field-magnets in order to supply the exciting current, each armature having its own commutator; machines on this plan were devised by Ladd[1] and by O. and F. H. Varley[2]; (2) a few of the armature coils may be connected up separately to a special commutator to supply an exciting current. Such systems were devised by Wilde, Holmes, and Lontin, about the year 1868 or 1869, in order to make their alternate-current machines excite themselves. Holmes described a machine having twenty helices in the armature, ten of which supplied alternate currents to the lamps, whilst the remaining ten, or any part of them, could be so connected up through a special commutator as to supply the exciting current to the field-magnets. Ruhmkorff attained the same end by winding a second wire upon the Siemens (shuttle-wound) armature, which then was provided with a

FIG. 43.



SEPARATE-CIRCUIT SELF-EXCITING DYNAMO.

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[1] *Phil. Mag.*, xxxiii. 544, 1867.

[2] Specification of Patent, 2525 of 1869.

commutator at each end. Winkler's dynamo[1] is internally self-excited by a second separate winding. The effect of the separate-coil method of excitation is almost identical with that of the shunt method, but it has the advantage that the current thus taken off for magnetizing may be taken at a low voltage; this being preferable in the case of machines for high voltages. For machines working at 1000 volts and over, the cost of the fine wire for winding a shunt would be prohibitive.

Any of the five systems enumerated may be applied in direct-current machines. For alternate-current machines, neither series winding nor shunt winding is applicable. Each of these five systems of exciting the field-magnetism has its own merit for special cases, but none of them is perfect. Not one of these methods will ensure that, with a uniform speed of driving, either the electric pressure at the terminals or the current shall be constant, however the resistances of the circuit are altered.

If all the lamps in the circuit of a dynamo were required to be kept alight, all being turned on and turned off at once—in other words, if the output of the machine were constant—it would matter little how the magnetism of the field-magnet was excited, whether in main circuit or in shunt, provided the speed were kept constant. But for systems with a variable number of lamps, none of the simple methods of excitation enumerated above will insure regularity of pressure in the electric supply.

But though theory tells us that none of these systems is perfect, theory does not leave us without a guide. Thanks to various inventors, we have been taught how to combine these methods so as to secure in practice a machine which shall, when driven at a constant speed, give out its current at a constant pressure. These methods are carefully developed in Chapter XI. They are briefly described here also, so as to complete our summary of the methods of exciting the field-magnets.

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[1] *Electrical World*, xvii. 455, 1891.

COMBINATION METHODS.

The discovery of the method of rendering a dynamo machine automatically self-regulating when driven at a uniform speed, is due to M. Marcel Deprez, and is a result arising from the study of the diagrams of the characteristic curves of dynamos.[1] There are two distinct cases for which self-regulation is required.

As the first function of a dynamo in practice is to feed with sufficiency and regularity a system of lamps, and as those lamps are usually in practice[2] arranged either in parallel or in series, it is clear that in the former case *a constant electric pressure or "difference of potentials"* between the mains, and in the latter *a constant current* is required.

Suppose a dynamo to have an armature, without demagnetizing reactions, of zero internal resistance, and to have its field-magnets excited from some independent constant source. At a constant speed it would give a constant potential at its terminals whatever the resistance in the circuit. But if it has internal resistance, the external pressure will be less than the whole electromotive-force, and the discrepancy will be greater according as the internal resistance and the current are greater. Any resistanceless, separately-excited, or shunt dynamo would thus be self-regulating.

Now it is, we know, impossible to have an armature the resistance of which is zero. But if, knowing the resistance of the armature of our dynamo, we find out what additional magnetizing power is necessary to increase the working electromotive-force of the dynamo, so that the net electromotive-force (after discounting the part needed to overcome the internal resistance) shall be constant, and then, having found it out, provide for this variable part of the magnetization by putting on coils in series, our dynamo thus reinforced will act as if it had no internal resistance, and will give, within certain limits, a constant difference of potentials at its terminals.

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[1] See *La Lumière Électrique*, Dec. 3, 1881; and Jan. 5, 1884.

[2] Occasionally incandescent lamps are arranged with two, three, or more lamps in series, a number of such series being united in parallel across mains that are kept at a constant pressure. Less frequently a few lamps all in parallel with one another are inserted in the circuit of a series of arc lamps through which a current of constant strength is maintained. In any case, distribution must fall under one or other of the two cases considered.

For distribution *at a constant pressure*, we must have, therefore, dynamos in which there is a combination of *series* coils with some auxiliary independent constant excitation.

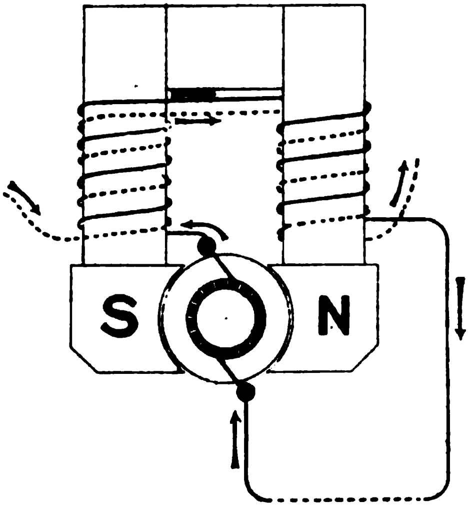
On the other hand, if a shunt dynamo were constructed, with an armature of considerable resistance, the electromotive-force which it would develop at a constant speed, would be nearly proportional to the external resistance, for doubling the external resistance would very nearly double the proportion of current thrown round the shunt, and therefore (always assuming the iron cores to be far from saturation) the magnetism of the field-magnet would be doubled; in other words, there would be an approximately constant current. In this case, a high internal resistance in the armature would not be economical, and the output of the machine would be very small in proportion to its weight; moreover, its magnetic state would be one of great instability. Consequently, it has been hitherto found impracticable to devise any mode of compound winding which will be self-regulating for a constant current. Other modes of regulation are resorted to in the case of machines for arc-lighting for which a constant current is needed. These are considered in Chapters XVII. and XXVII.

COMBINATIONS TO GIVE CONSTANT PRESSURE.

(1) *Series and Separate* (*Deprez*).—This method, illustrated in Fig. 44, can be supplied to any series dynamo, provided the coils are such that a separate current from an independent source can be passed through a part of them, so that there shall be an initial magnetic field, independent of the main-circuit current of the dynamo. When the machine is running, the electromotive-force producing the current will depend partly on this independent excitation, partly on the current's own excitation of the field-magnets. If the

machine be run at such a speed that the quotient of the part of the electromotive-force due to the self-excitation, divided by the strength of the current, is numerically equal to the internal resistance of the machine, then the electromotive-force in the circuit will be constant, however the external resistances are varied. M. Deprez has further shown that this velocity can be deduced from experiment, and that, when the critical velocity has once been determined, the machine can be adjusted to work at any desired electromotive-force by varying the strength of the separately-exciting current to the desired degree.

Fig. 44.



Combination of Series and Separate.

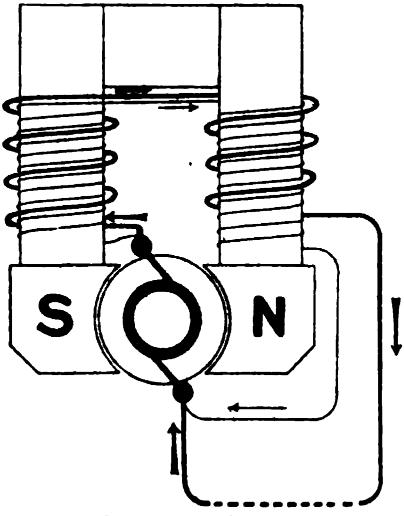
(2) *Series and Magneto* (*Perry*).—The initial electromotive-force in the circuit required by Deprez's theory, need not necessarily consist in there being an initial magnetic field of independent origin. It is true that the addition of a permanent magnet, to give an initial partial magnetization to the pole-pieces of the field-magnets, would meet the case to a certain extent; but Professor Perry has adopted the more general solution of introducing into the circuit of a series

dynamo a separate magneto machine, also driven at a uniform speed, such that it produces in the circuit a constant electromotive-force equal to that which it is desired should exist between the leading and return mains.

This arrangement may be varied by using a shunt-wound exciter, the magnets being, as before, included in the part of the circuit outside the machine. The combination of a permanent magnet with electromagnets in one and the same machine, is much older than the suggestions of either Deprez or Perry, having been described by Hjorth in 1854.

(3) *Series and Shunt.*—A dynamo having its coils wound, as in Fig. 45, so that the field-magnets are excited partly by the main current, partly by a current shunted across the brushes of the machine, has been used for some years past. An arrangement used by Brush[1] from 1878 made the machine

FIG. 45.



SERIES AND SHUNT.

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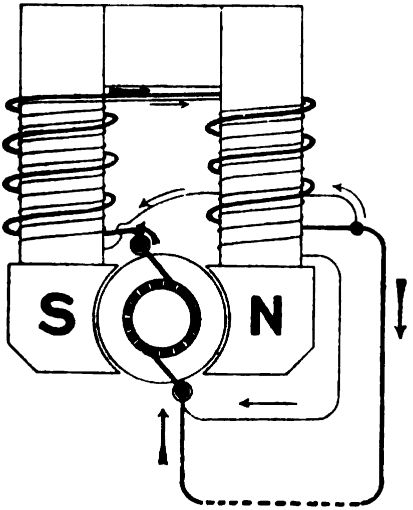
[1] The shunt part of the circuit, originally called the "teazer," was adopted at first in machines for electro-plating, with the view of preventing a reversal of the current by an inversion of the magnetization of the field-magnets, but was retained in some other patterns of machine on account of its usefulness in "steadying" the current.

into one that was very nearly self-regulating, there being less than one volt of variation in the pressure within a wide range of current. If the shunt coils be comparatively few, and of high resistance, so that their magnetizing power is small, the machine will give approximately a uniform pressure of but few volts; whereas, if the shunt be relatively a powerful magnetizer, as compared with the few coils of the main circuit, the machine will be adapted for giving a constant pressure of a great number of volts; but, as before, each case will correspond to a certain critical speed, depending on the arrangements of the machine. The arrangement with shunt and series coils is commonly known as a *compound winding*.

(4) *Series and Long Shunt.*—In 1882 the author proposed to give this name to a combination closely resembling the preceding, which had not then, so far as he was aware, been actually tried for this purpose, though it had been, like the preceding, described by Brush. If, as in Fig. 46, the magnets are excited partly in series, but also partly by coils of finer wire, connected as a shunt *across the whole external circuit*, then

FIG. 46.



SERIES AND LONG SHUNT.

the combination should be more applicable than the preceding to the case of a constant electromotive-force, for the current through the long-shunt winding will be more constant than that through a short shunt connected across the brushes.

In 1882 it was the author's opinion that although the last two combinations were not such perfect solutions of the problem as those which precede, they were more likely to find an immediate application,[1] since they can be put into practice upon any ordinary machine, and do not require, as in the first two combinations, the use of separate exciters, or of independent magneto machines. This opinion has been fully justified in the great progress made subsequently in the "compound" self-regulating machines.

(5) *Series and Separate-Coil.*—This method has not, apparently, been tried for direct-current dynamos. For alternate-current dynamos a modification of it has been tried by Zipernowsky with success, the "series" or main-circuit excitation being, in this case, replaced by an excitation derived from the main circuit by means of a small transformer. This system is explained in Chapter XXV.

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[1] The invention of the "series and shunt" winding is claimed for several rivals. Brush undoubtedly first used it commercially, but whether with any knowledge of all its advantages is doubtful. It has also been claimed by Mr. S. A. Varley on the strength of the machine described in his patent specification, No. 4905 of 1876, in which there were two circuits both of different resistance, both having coils wound on the field-magnets, and both going to the lamp. He has obtained a decision in the Scottish law courts that this strange arrangement anticipated that described by Brush. Compound winding was, however, described in 1871 by Sinsteden, in *Pogg. Annalen* (*Supplement-Band*, v.), 651. It was mentioned as having some advantages by Sir C. W. Siemens in *Philosophical Transactions*, March 1880. It is also claimed for Lauckert (see note by M. Boistel, p. 100 of his translation of first edition of this work); Paget Higgs (*Electrical Review*, xi. 280, and *Electrician*, Dec. 23, 1882); J. W. Swan, see Bosanquet (*ib.*, Dec. 9, 1882); J. Swinburne (*ib.*, Dec. 23, 1882); S. Schuckert (*ib.*, Oct. 13, 1883). It is claimed in America by Edison; and it has been patented by Messrs. Crompton & Kapp (*ib.*, June 9, 1883). See also Hospitalier (*L'Électricien*, No. 20, 1882). Students should also consult a series of articles in *The Electrician*, vol. x., beginning Dec. 16, 1882, by Mr. Gisbert Kapp. Further, they should see a paper by Dr. Louis Bell in the *Electrical World*, xvi. 383, 1891.

CHAPTER IV.

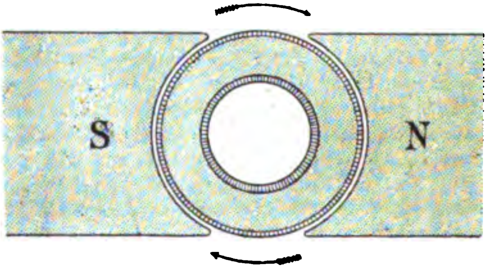
ACTIONS AND REACTIONS IN THE ARMATURE.

IN this chapter we shall deal mainly with continuous-current dynamos with armatures of either ring or drum type, and having a simple magnetic field such as is furnished by the two-pole field-magnet so common in machines of this class.

For the sake of clearness we will suppose the armature (as viewed from the end to which the commutator is affixed), to be rotating right-handedly; and we will further suppose that the north-pole of the field-magnet is situated on the right hand, as in Figs. 39 to 46, so that the magnetic lines pass through the armature-core from right to left. We shall further suppose that the coils on the armature-cores are wound right-handedly. Taking this as a standard case it is afterwards very easy to see how a change in any one of these conditions will affect the induction of electromotive-force.

In Fig. 47 these points are illustrated by an end-view of a ring-armature. The magnetic lines proceeding from the N-pole will cross the adjacent gap-space from right to left, and enter the iron core of the armature; traversing this (as

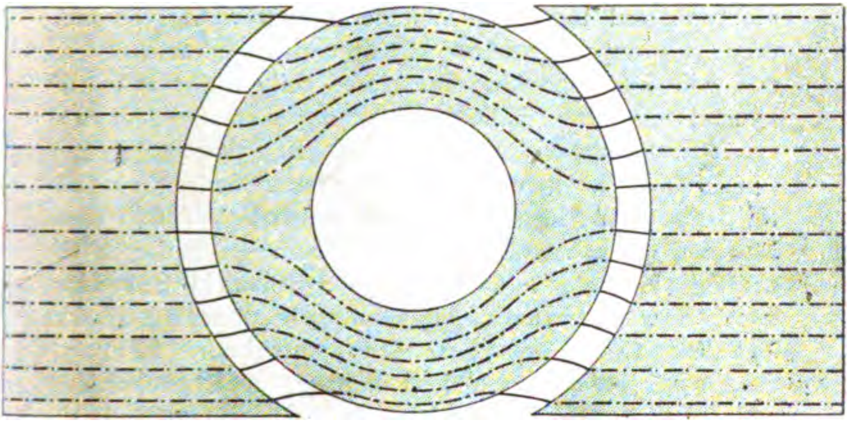
FIG. 47.



END-VIEW OF ARMATURE BETWEEN TWO-POLE FIELD-MAGNET.

in Fig. 48), they will then cross the other gap-space on the left and enter the S-pole of the field-magnet. The copper wires or conductors of the armature as each rises successively in the left-hand gap will cut these magnetic lines. Each conductor will emerge at the top of the gap, will move over the highest part of the armature from left to right, and in descending the gap-space on the right will again cut the magnetic lines. If we now apply the rule laid down on p. 22,

FIG. 48.



MAGNETIC LINES OF TWO-POLE DYNAMO (UNDISTURBED BY ANY CURRENT IN ARMATURE).

we shall find that the directions of the induced electromotive-forces in these rotating conductors will be as follows :—In all the conductors as they *ascend* through the left-hand gap-space, the direction of the induced electromotive-force is *toward* the observer—whilst in all those that are *descending* the other gap-space on the right the induced electromotive-forces will be directed *from* the observer. If we assume that these electromotive-forces are actually producing currents,[1] then we may say that the currents flow toward the observer in the conductors which are rising in the left gap-space; and from the observer in those that are descending the right gap-space. If the armature is wound as a ring, the currents which come in one direction in the gap-space return in the other direction down the inside of the ring. If the armature is wound as a drum, then the currents simply cross at the end of the core through connecting conductors provided for the purpose.

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[1] In all dynamos, when used as *generators*, the currents being set up by the electromotive-forces are of course in the *same direction* as the electromotive-forces which impel them. But it must be remembered that in the case of machines that are used as *motors* the currents are being sent in by superior electromotive-forces from outside, and that the induced electromotive-forces in the motor's armature, are always in an *opposite direction* to that of the current that is flowing.

Now consider the way in which the coils on the armature are connected together. Whether wound as ring or drum they are grouped symmetrically around a symmetrical core, and united together into one closed coil; whilst at regular intervals along the windings, connecting pieces lead down to the separate bars of the commutator. Fig. 34, p. 40, shows a simple ring-winding, consisting of 32 turns of wire grouped in eight "sections" or groups, each consisting of four turns. The end of each section is joined to the beginning of the next, all the way round. There are eight bars in the commutator, and each section of the winding is connected down at its ends to two adjacent bars of the commutator. In Fig. 34, the brushes are represented as making contact respectively with the highest and lowest bars of the commutator. As the windings on the ring are right-handed a little consideration will show, in accordance with the preceding paragraphs, the induced currents in the ascending windings on the left-hand half of the ring will all be climbing from the lowest point to the highest; and also the currents in the right-hand half of the ring will also be climbing from the lowest point to the highest. These two currents will unite at the top bar of the commutator, and will flow together into the upper brush (which will accordingly be deemed the positive brush), and thence will go to supply the external circuit; after which the current will return to the lower, or negative brush, and will there re-enter the armature at the lowest bar of the commutator, dividing again into two parts and flowing up the two halves of the winding as before. If the conductors on the armature were wound (or connected) left-handedly, the lower brush would be the positive one, and the upper the negative. All the preceding argument would equally apply to a drum-winding, but, owing to the overlapping of the two halves of the windings, the paths of the current would not be quite so obvious.

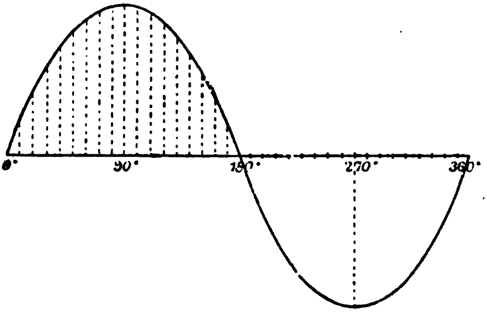
It will be noted that the current after having entered the armature coils and divided into its two paths goes from section to section without going down into any of the commutator bars until both streams unite at the other side and pass down into the bar of the commutator which is for the moment passing under the brush. At those moments when one of the commutator bars is just leaving contact with a brush, and another one is coming into contact with it, the brush will rest on two adjacent bars and will momentarily short-circuit one section of the coils. While this lasts the two streams that come through the two halves of the winding will flow respectively to the two bars of the commutator, and will thus unite by both flowing into the same brush.

It is evident that if the magnetic lines in the gap-space are more closely crowded together in one part than in another, the electromotive-forces induced in the separate windings as they cut these magnetic lines will be of unequal amount; the greatest electromotive-force being generated in those conductors which are passing through that part of the magnetic field where the lines are crossing the gap most densely. But whatever the electromotive-forces are in the individual conductors, since these are all united together end to end, it will be obvious that the total electromotive-force of either half of the winding, from brush to brush, will be the sum of the electromotive-forces in the separate coils. As this is a point of importance it must be followed out with some care.

INDUCTION IN A UNIFORM HORIZONTAL MAGNETIC FIELD.

In considering the case of an ideal simple dynamo, it was shown that the induction in the rotating loop or coil was zero at the position where it lay in the diameter of commutation, and that the induction increased (as the sine of the angle) to its maximum value at about 90° (see Fig. 18, p. 32). This is of course true for the ideal case of the magnetic lines going straight across horizontally with equal density everywhere. In actual dynamos the distribution of magnetic lines in the gap is different, not always symmetrical, as we shall see. Returning to the ideal case, Fig. 49, which presents a curve

FIG. 49.

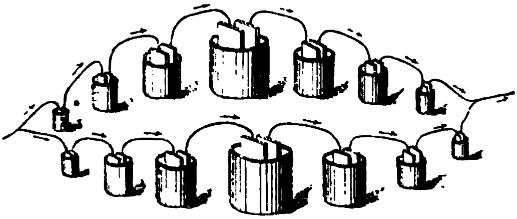


CURVE OF INDUCED ELECTROMOTIVE-FORCE.

of *sines*, will serve to represent, by the height of the curve, the amount of induction going on in an armature at every 10° round the circle. If there are, for example, thirty-six sections in a ring armature, so that the sections are spaced out at 10° apart, the least active sections will be those at 0° and 180°, whilst the most active are those at 90° and 270°. But in all the ordinary "closed-coil" armatures, the separate sections are connected together so that any electromotive-force induced in the first section is added on to that induced in the second, and that in the third is added to these two, and so on all the way round to the brush at the other side. The separate electromotive-forces are added together just as are the separate electromotive-forces of a battery of voltaic cells united in series. A ring of battery cells united in series, but having one-half the cells set so that the current in them tends to run the other way round the ring, forms a not inapt illustration of the inductions in the sections of a ring armature. If it could be indicated that those sections which are at 90° from the brushes are much more powerful in their inducing effect than those that occupy positions near the brushes, the analogy would be still more perfect.[1]

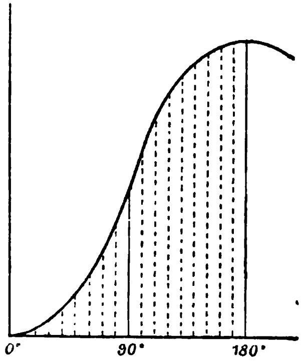
Now, knowing how the induction in individual coils or sections rises and falls round the ring, let us inquire what this will result in when we add up the separate electromotive-forces, so as to find the total effect. We shall have to add up the effects of all the sections round, from the negative brush at 0° on one side, to the positive brush at 180° on the other side: and the result will be the same in each half of the ring, because of symmetry. Suppose we take the side from 0° by 90° to 180° (on the left in Figs. 20 and 47). If we look at the curve given above (Fig. 49), we shall see that as the heights of the dotted lines represent the amount of induction, the total effect will be got by adding up the lengths of all those from 0° to 180°; and of course, the sum is equal to the sum of the negative lengths between 180° and 360°. But we may do the thing in another way, which beside giving us the final total, will show

FIG. 50.



RING OF CELLS: THE TWO HALVES IN PARALLEL.

FIG. 51.



INTEGRATED CURVE OF POTENTIALS.

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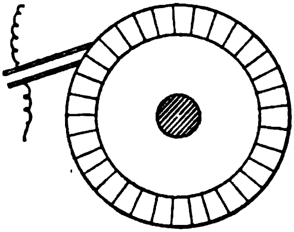
[1] In Fig. 50 the middle cells of each row are drawn larger to suggest this; only, unfortunately, *large* cells do not possess a higher electromotive-force than small ones, though they have less resistance internally.

us how the sum grows as each length is successively added on. We should find that the sum grew slowly at first, then rapidly, then slowly again as it neared its highest value. The sum of the effects would grow, in fact, in a fashion represented on a reduced scale in the curve of Fig. 51. This process of adding up a continuously-varying set of values is called by mathematicians integrating. Fig. 51 is got by integrating the values of the curve Fig. 49 between the limits of 0° and 180°. Now in the actual dynamo this integration is effected by the very nature of things, in consequence of the fact that each section is united to those on either side of it.

It is possible to investigate by experiment both these effects;[1] the induction in the individual coils, and the total or integrated potential. Several methods have been suggested for measuring the electromotive-forces, and as each has some advantages, they will be separately described.

S. P. Thompson's Method.—The electromotive-force induced in a single section as it passes any particular position, may be examined by means of a voltmeter or potential-galvanometer in the following way. Two small metal brushes are fixed to a piece of wood at a distance apart equal to the width between two consecutive bars of the commutator. These brushes are united by wires to the voltmeter terminals, so that any difference of potentials between them will be indicated on the dial of the instrument. The two brushes are placed against the collector, as shown in Fig. 52, while it rotates; and as they can be applied at any point, they will give on the voltmeter an indication which measures the

FIG. 52.



METHOD OF EXPERIMENTING AT COMMUTATOR OF DYNAMO.

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[1] For some investigations made by the author, the reader is referred to the Author's *Cantor Lectures* delivered in 1883 before the Society of Arts, and which are also described in the earlier editions of this book. The reader should refer to curves of induction obtained by Gaugain (see *Annales de Chimie et de Physique*, 1873), and by Isenbeck (see *Elektrotechnische Zeitschrift*, *Aug.* 1883).

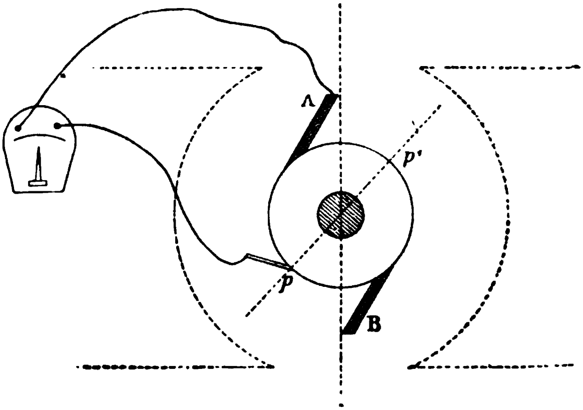
amount of electromotive-force in that section of the armature which is passing through the particular position in the field corresponding to the position of the contacts. The author found, in the case of a small Siemens dynamo which he examined, that the difference of potential indicated was almost *nil* at the sections close to the proper brushes of the machine, and was a maximum about half-way between. In fact, the difference of potentials rose most markedly at 90° from the usual brushes, or precisely in the region where, as seen in Fig. 49, the induction is theoretically at its highest point, and where, as seen in Fig. 51, the slope of the curve of total potential is greatest.

Method of Shifting Armature.—After the experiment above detailed, the author experimented on his Siemens dynamo in another way. The machine was dismounted, and its field-magnets separately excited. Two consecutive bars of the commutator were then connected with a reflecting galvanometer having a moderately heavy and slow-moving needle. A small lever clamped to the commutator allowed the armature to be rotated by hand through successive angles equal to 10°, there being thirty-six bars to the commutator. The deflections obtained, of course measured the intensity of the inductive effect at each position. The result confirmed those obtained by the method of the two wire brushes.

Mordey's Method.—The rise of the totalized (*i.e.* "integrated") potential round the armature can be measured experimentally by a method first suggested by Mr. W. M. Mordey, and also involving the use of a voltmeter. One terminal of a voltmeter was connected to one of the brushes, A, of the dynamo (Fig. 53), and the other terminal was joined by a wire to a small pilot brush, *p*, which could be pressed against the rotating collector at any desired part of its circumference. In a well-arranged continuous-current dynamo thus, if one measures the difference of potential between the negative brush and the successive bars of the commutator, one finds that the potential increases regularly all the way round the armature, in both directions, becoming a maximum at the opposite side where the positive brush is. Mr. Mordey found that this distribution is irregular in badly designed machines.

The author then made the suggestion that these indications might with advantage be plotted out round a circle corresponding to the circumference of the commutator. Figs. 54 and 55, which are reproduced from his Cantor Lectures, serve to show how the potential in a good Gramme machine rises gradually from its lowest to its highest value.

FIG. 53.



MORDEY'S METHOD OF EXPLORING THE POTENTIALS AROUND THE COMMUTATOR.

FIG. 54.

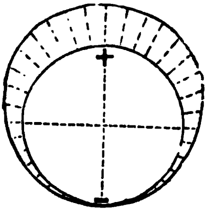
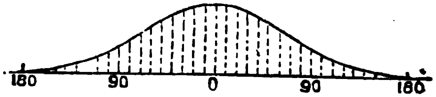


DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF GRAMME DYNAMO.

FIG. 55.



HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF GRAMME DYNAMO.

It will be seen that, taking the negative brush as the lowest point of the circle, the potential rises perfectly regularly to a maximum at the positive brush. The same values as are plotted round the circle in Fig. 54 are plotted out as vertical ordinates upon the level line in Fig. 55, which is nothing else than Fig. 51 completed for both halves of the commutator. Fig. 51 is, however, a theoretical diagram of what the distribution ought to be, whilst Fig. 55 is an actual record taken from an "A" Gramme. If the magnetic field in which the armature rotated were uniform, this curve would be a true "sinusoid," or curve of sines. The steepness of the slope of the curve at different points will enable us to judge of the relative idleness or activity of coils in different parts of the field. The points marked + and − are close to the points of least sparking, or *neutral points*.

The rise of potential is not equal between each pair of bars, otherwise the curve would consist merely of two oblique straight lines, sloping right and left from the neutral point. On the contrary, there is very little difference of potential between the commutator-bars immediately adjoining either of the neutral points. The greatest difference of potential occurs where the curve is steepest, at a position nearly 90° from the brushes, in fact, at that part of the circumference of the commutator which is in connexion with the coils that are passing through the position of best action. Were the field perfectly uniform and parallel, the number of lines of force that pass through a coil ought to be proportional to the sine of the angle which the plane of that coil makes with the resultant direction of the lines of force in the field, and the rate of cutting the lines of force should be proportional to. the cosine of this angle. Now the cosine is a maximum when this angle = 0°; hence, when the coil is parallel to the lines of force, or at 90° from the brushes, the rate of increase of potential should be at its greatest—as is very nearly realized in the diagram of Fig. 55, which, indeed, is very nearly a true "sinusoidal" curve. Such curves, plotted out from measurements of the distribution of potential at the commutator, show not only where to place the brushes to get the best effect, but enable us to judge of the relative "idleness" or "activity" of coils in different parts of the field, and to gauge the actual intensity of different parts of the field while the machine is running.

As we shall see, the current in the armature reacts on the magnetic field, and distorts the distribution of magnetic lines in the gap-space. If the brushes are badly set, or if the pole-pieces are not judiciously shaped, the rise of potential will be irregular, and there will be maxima and minima of potential at other points. An actual diagram, taken from a dynamo in which these arrangements were faulty, is shown in Fig. 56 and again is plotted horizontally in Fig. 57; from which it will be seen, not only that the rise of potential was irregular, but that one part of the commutator was more positive than the positive brush, and another part more negative than the negative. The brushes, therefore, were not getting their proper difference of potential; and in part of the coils, the currents were actually being forced against an opposing electromotive-force.

FIG. 56.

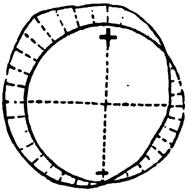
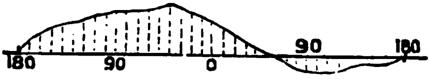


DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF A BADLY-ARRANGED DYNAMO.

FIG. 57.



HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF FAULTY DYNAMO.

This method of plotting the distribution of potential round the commutator has proved very useful in practice, and elucidates various puzzling and anomalous results found by experimenters who have not known how to explain them.

Curves similar to those given can be obtained from the commutators of any continuous-current dynamo having a closed-coil armature. The open-coil machines used in arc lighting give widely different curves owing to the peculiar arrangements of their commutators. It is of course, not needful in taking such diagrams that the actual brushes of the machine should be in place, or that there should be any circuit between them, though in such cases the field-magnets must be separately excited. It should also be remembered that the presence of brushes, drawing a current at any point of the collector, will alter the distribution of potential in the collector; and the manner and amount of such alteration will depend on the position of the brushes, and the resistance of the circuit between them.

Curves showing the actual distortions due to the armature reaction have been given by von Gaisberg[1] for a Schuckert dynamo, by Kohlrausch[2] for a Lahmeyer dynamo, and by M. E. Thompson[3] for a Thomson-Houston dynamo; also by Ryan (see below).

Swinburne's Method.—An elegant modification of the preceding method consists in connecting a high-resistance wire across the terminals of the machine, and finding by a detector galvanometer the positions along this wire of the points which have the same potential as that of the pilot-brush on the commutator. Being a zero method it is very accurate; and it dispenses with the voltmeter, which for the preceding method must be accurate over a wide range.

Joubert's Method.—Another mode of examining the electromotive-force induced at every successive point in the rotation was devised by M. Joubert,[4] who placed on the shaft of the dynamo a pair of insulated metal collars connected to the ends of the armature winding; each collar having a projecting contact piece which at each revolution made a moment contact against a spring. The moment at which this occurred depended upon the position of the contact springs, which could be adjusted to different points, and thus enable measurements to be made of the instantaneous values of the electromotive-force at all different positions of the armature. Joubert's method has been used, with some modifications, by Mordey and Raworth[5] and by Ryan.[6]

Mordey's Statical Method.—Another method, applicable to machines at rest and without currents in the armature, consists in separately exciting the field-magnets, while the armature coils, or any one of them, are connected to a suitable ballistic galvanometer, and observing the throw caused by the sudden turning off of the current in the exciting circuit. If this is done in a number of successive positions of the armature, relatively to the field-magnet, a measure is obtained of the intensity of the magnetic flux, corresponding to each position of the armature, and the result may be plotted out in a curve exhibiting the distribution of magnetism in the field. This distribution is however perturbed, as we shall see, when the machine is running by the current in the conductors of the armature.

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[1] *Elektrotechnische Zeitschrift*, vii. 67, Feb. 1886.

[2] *Centralblatt für Elektrotechnik*, ix. 419, 1887.

[3] *Electrical World*, xvii. 392, 1891.

[4] *Annales de l'École Normale*, x. 131, 1881.

[5] *Journal Inst. Electrical Engineers*, xviii. 670, 1889.

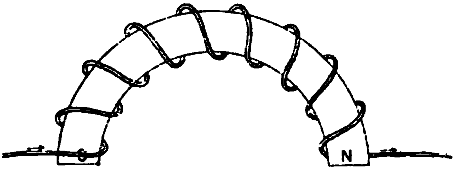
[6] *Trans. Amer. Instit. Electrical Engineers*, vii. 3, 1890.

REACTIONS DUE TO THE CURRENTS IN THE ARMATURE.

When a dynamo is running, a set of entirely new phenomena arises in consequence of the magnetic and electric reactions set up between the armature and the field-magnets, and between the separate sections of the armature coils. The current circulating in the armature windings produces magnetizing effects which interfere with those of the exciting currents of the field-magnet. In addition to this there may also be eddy-currents in the masses of metal which will perturb the magnetic field. The reactions of the running armature manifest themselves in several ways, the more important of which are (*a*) a tendency to cross-magnetize the armature; (*b*) a tendency to spark at the brushes; (*c*) hence the necessity of shifting the brushes through a certain angle to such a point that sparking disappears; (*d*) a consequent tendency for the armature current to demagnetize; (*e*) variations of sparking, and consequently of the neutral points, when the amount of current drawn from the machine is altered; (*f*) heating of armature cores and coils; (*g*) heating of the pole-pieces of the field-magnets; (*h*) a consequent discrepancy between the quantity of mechanical horse-power imparted to the shaft and the electric horse-power furnished in the electric circuit. The nature of these reactions demands careful attention.

Cross-magnetizing tendency of Armature Current.—We have seen (pp. 66, 67, and Fig. 50) that any closed-coil armature may be regarded as acting like a double voltaic battery, the two sets of coils acting like two rows of cells united "in parallel." We have now to show that a ring armature may be regarded also as a double magnet. Suppose a semi-ring of iron to be surrounded, as in Fig 58, by a coil

FIG. 58.

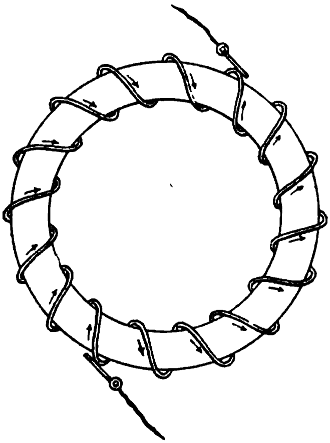


POLES OF HALF-RING.

carrying a current, it will become, as every one knows, a magnet having a N. pôle at one end, and a S. pole at the other. If a complete ring be similarly over-wound, but with an endless winding, and if then electric currents from a battery or other source are introduced into this coil at one point, flowing round the two halves of the ring to a point at the other side, and then leave the coil by an appropriate conductor, each half of the ring will be magnetized. There will be, if the currents circulate, as represented by the arrows in Fig. 59, a double S. pole at the point where the currents enter, and a double N. pole at the place where the currents leave (compare with p. 123). The currents circulating in a Gramme ring, will therefore tend to magnetize the ring in this fashion. Let us see how such a magnetization is distributed inside the iron itself. Fig. 60 shows the general course of the magnetic lines of force as they run through the iron; where they emerge into the air are the effective poles of the ring regarded as a magnet. Fig. 60 should be very carefully compared with Fig. 59. It will be noticed that though the majority of the lines of force pass externally into the air at the outer circumference, a few of the lines of force find their way across the interior of the ring, from its N. to its S. pole. This part of the magnetic field would in an actual dynamo be deleterious if the number of lines of force were not in reality few. The presence of the external masses of iron at the polar parts of the field-magnet tends to cause these magnetic lines to find their way externally.

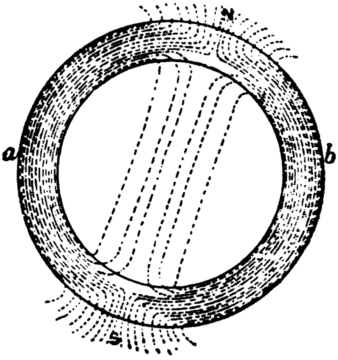
It is evident that this cross-magnetizing effect will produce a distortion of the magnetic field in the pole-pieces and in the gap-space; and it would only slightly diminish the electromotive-force of the machine if the brushes were to remain at the ends of a diameter exactly symmetrically between the two poles of the field-magnet. For reasons presently to be considered this is not possible. To obviate sparking the brushes have to be displaced into an angular position, the diameter of commutation being oblique when the brushes are so set at the neutral points; and when this is done the armature current produces, as we shall see, not only a cross-magnetizing effect, but also a demagnetizing effect; and this weakens the electromotive-force.

FIG. 59.



CIRCULATION OF CURRENT AROUND RING ARMATURE.

FIG. 60.



MAGNETIC FIELD DUE TO ARMATURE CURRENT.

Fig. 61 represents[1] the magnetic flux through an armature at rest, when the field-magnets are separately excited. The width of the gap-space is exaggerated, and the conducting wires both on the armature and on the field-magnet are shown in section as if consisting of a single layer of large round wires. Wires in which a current flows *toward* the observer are distinguished by a central dot. Wires in which a current flows *from* the observer are distinguished by a cross.

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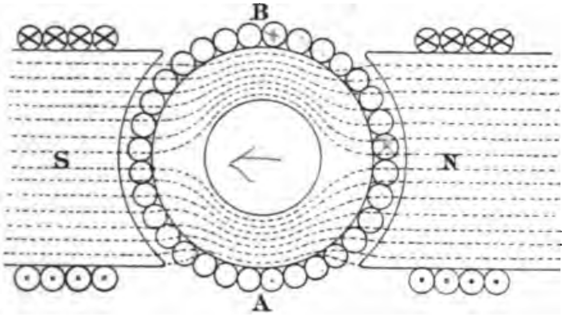
[1] Figs. 61, 62, 63, and 69 are taken, with some modification, from Esson's paper in *Journal Inst. Electrical Engineers*, xix. 135, 1890.

Fig. 61.

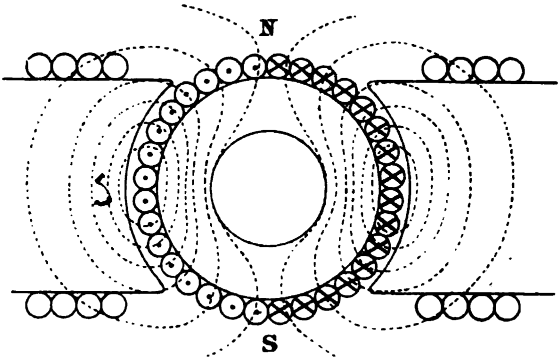


Magnetic Flux through Armature, when no Current is Flowing.

The reader may think of the dot as representing the point of an arrow advancing towards him; whilst the cross may represent its retreating tail. Wires carrying no current are left blank. It will be noticed that the magnetic lines are fairly uniformly distributed both in the gap-spaces and in the polar portions of the field-magnet. The armature is drum-wound, the wires being only on the outside: the magnetizing effect of a current in it will be of the same kind as that traced out above in the case of a ring-wound armature, though less in degree.

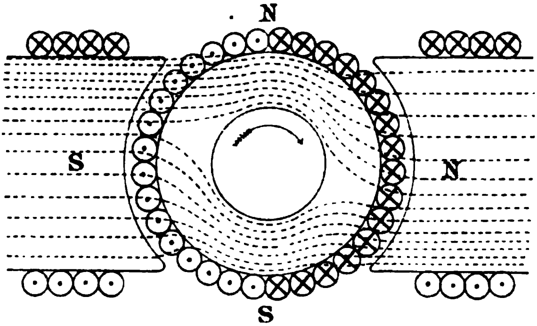
Suppose now the exciting current in the field-magnet coils to be removed, and a current sent through the armature coils only, so as to imitate the effect of the current generated by the machine when running. If it is to do this, and if the armature connexions are in right-handed order, and the machine rotating right-handedly, the currents in both sets of windings will tend to climb toward the top, the upper brush being the positive brush, and the double-pole created there will be a north-pole. Suppose the brushes by which the current enters and leaves to be set respectively at the highest and lowest points, as in Fig. 62; then the dotted lines may be taken as representing the flow of magnetic lines through the system. Since the number of such magnetic lines depends upon the goodness of the magnetic path which they have to follow, it is clear that the cross-field produced by a given current, flowing in a given set of conductors, will be greater the narrower the gap-space, and

FIG. 62.



CROSS-MAGNETIZING EFFECT OF THE ARMATURE CURRENT.

FIG. 63.



JOINT MAGNETIZING EFFECT OF CURRENTS IN FIELD-MAGNET AND ARMATURE (no lead).

the wider the arc spanned by the polar masses of iron[1] on either side.

But in an actual dynamo, when generating a current, both these magnetizing actions are going on at once. If we superpose Fig. 62 on Fig. 61 we shall obtain an approximate picture of the state of things, as Fig. 63. We supposed that the brushes were set to touch at two points on the vertical diameter. The field-magnets tend to magnetize the ring so that its extreme left point is a N. pole, and the currents tend to magnetize it so that its highest point, where the brush is, is a N. pole. The consequence of this will be a resultant magnetization in an oblique direction. Draw a line O F (Fig. 64) to represent the magnetizing force due to the field-magnets, and a line O C at right angles to represent the magnetizing force due to the armature current, then the diagonal O R of the parallelogram will represent the direction of the resultant magnetization. Draw a circle round O, and the point N will show how far the resultant induced magnetism is shifted round from the horizontal line. The magnetism is thus distorted in the direction of the rotation (in motors it is distorted the other way) as if the rotation of the armature had actually dragged the magnetism round a little. The position of maximum potential will also be shifted a little in the direction of the rotation. Now for reasons to be shortly discussed, when the magnetism is thus distorted, the *neutral points* (*i.e.* the points to which the brushes must be set so as to reduce sparking to a minimum) are found to have been also shifted forward. If for the present we assume that the brushes must be advanced through an angle equal to that through which the resultant magnetization has been turned, then O C must be altered till it is at right angles to O N. But shifting O C will itself alter N a little. We can find out easily the new position. On O F (Fig. 65) describe a semicircle, and set off F R, equal to the length that O C is to be, as a chord. Draw O C parallel and equal to

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[1] Since these polar masses constitute the path by which the magnetic lines of the cross-field return on themselves, it is obvious that the cross-magnetization can be partially counteracted by dividing the polar masses by gaps running horizontally. See *Journal Inst. Electrical Engineers*, xx. 290, 1891.

F R; and draw also the diagonal O R as before. The angle C O N is now a right angle, and N is very nearly where it was before. If O V be a vertical line, then angle V O C = angle F O R is the angle of lead, and if O F represents the magnetizing force of the field-magnets, and O C that of the armature current, then

$$\frac{O\,C}{O\,F} = \sin C\,R\,O = \sin F\,O\,R,$$

or the sine of the angle of lead is proportional to the ratio of the two magnetizing forces.

FIG. 64

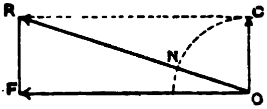
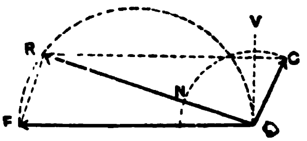
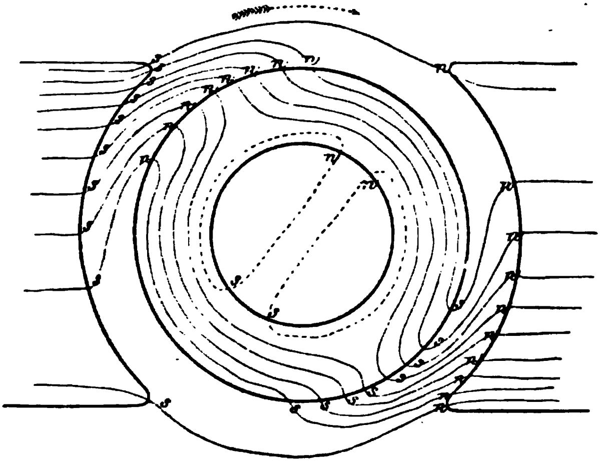


FIG. 65.



All this rearrangement of the lead is supposed to have been done in Fig. 66, which relates to a ring-wound dynamo. But a reference to Figs. 63 and 66, will also show that the magnetism of the armature reacts on the magnetism of the pole-pieces. The magnetic lines in the iron of the left pole-piece are crowded up towards the top corner, and in the right pole-piece are crowded toward the bottom, as if the polarity had been attracted upwards on one side and downwards on the other. The density of the field is completely changed from what it was in Fig. 61. The magnetic lines at the upper left side are crowded together and twisted across. The resultant N. pole of the ring—marked *n*, *n*, *n*, where the lines emerge from the ring—attracts the S. pole—marked *s*, *s*, *s*, where the lines enter the field-magnet—and the steam-engine which drives the dynamo has to do hard work in dragging the armature round against these attractions. The stronger the current in the armature coils, the stronger will be the poles in the armature, and the stronger will be the attraction of *n*, *n*, *n*, toward *s*, *s*, *s*; so the steam-engine must work still harder to keep up the speed. It will also be noticed in this figure which relates to a ring-wound machine that a *few* of the magnetic lines due to the current in the armature—two of them are shown dotted in the figure—leak across internally and contribute nothing to the external field. The oblique direction of this internal field marks the angle of lead of the brushes. It will be remarked that the innermost layers of iron of the ring are magnetized differently from the outermost, for the "*n*" pole of the outer layers of iron occupies a region lying obliquely on the left, while the "*n*" pole of the inner layers lies to the right of the highest point. All these phenomena—the shifting of the field—its concentration under the "leading" polar horn—its weakening under the "trailing" horn—the weak internal field—the discrepancy between the positions of the induced poles on the inner and outer sides of the ring, can all be observed in an actual dynamo. Fig. 67 shows the pattern produced experimentally in iron filings by placing a magnetized ring between the poles S N of a field-magnet, which would tend to induce in it poles n', s', and giving its own poles *n s*, the proper lead. It should

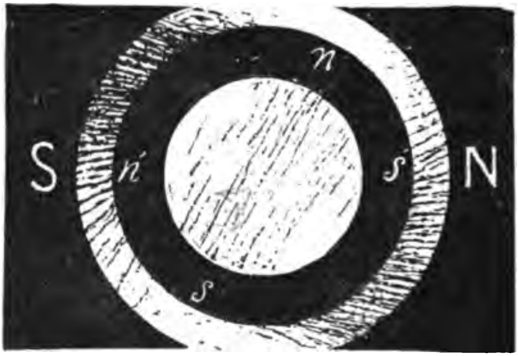
Fig. 66.



MAGNETIC REACTIONS BETWEEN FIELD-MAGNETS AND ARMATURE IN GENERATOR.

be compared with Figs. 63 and 66. It may perhaps be objected that in Fig. 66 the internal poles marked do not lie exactly at right angles to the external poles of the ring. Nor do they in actual dynamos. The position of the internal poles is determined by the lead given to the brushes, and ***the brushes are so set that the dynamo shall not spark.***

FIG. 67.



FIELD OF TWO-POLE DYNAMO.

In the case of drum-wound armatures, the phenomena, though of the same kind as with ring windings, are a little less easily traced. In consequence of the over-wrapping of the windings on the outside of the armature, the currents in some of the windings are partially neutralized in their magnetizing effect on the core by those that lie across them, and consequently the polarity due to the current is not so well marked as with ring armatures. Neither can there be any considerable internal field. In fact drum armatures are less liable to induction troubles of all kinds than are ring armatures. But, with these exceptions, the same considerations apply to drums as to rings.

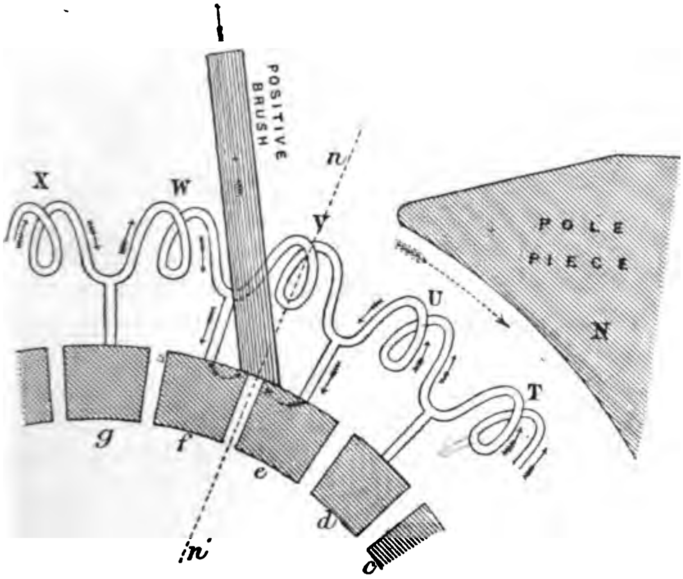
Neutral Points.—From the earliest time that dynamos have been used, engineers have found that, in order that the sparking may be a minimum, the brushes must be placed in certain positions, to be found by trial, called the ***neutral*** *points.* In ordinary two-pole dynamos the two neutral points lie at opposite ends of a diameter, which diameter is therefore called the *neutral line.* The term *diameter of commutation* ought to be reserved to denote the position actually occupied by the brushes, or by the coils that are passing the brushes, whether at the neutral point or not. Experience shows that in almost every case the neutral line is not exactly at right angles to the line joining the middles of the two pole-pieces, but lies obliquely across, being (in a generator) shifted round a few degrees in the direction of rotation. It was early found that in many machines the exact position of the neutral point was different according to the work that the dynamo was doing. If the brushes were set so as not to spark when a certain number of lamps were alight, then if the load of lamps was altered the machine sparked unless the brushes were adjusted to the corresponding neutral points. Hence arose the practice of mounting the brushes on *rockers* (see p. 35) by means of which their line of contact could be altered forward or backward to the neutral point. Great attention has naturally been paid by constructors to the practical problem how to get rid of variations in the angle of lead. On p. 71 it was stated that the neutral points lie close to the points of maximum positive and maximum negative potential on the commutator. But they are found not to coincide exactly with those points. At the point of maximum potential there is usually some sparking. The point of maximum potential has, as just shown, a forward lead, but the point of least sparking, the true *neutral* point, lies a little forward of this, this increased lead being due to another of the reactions now under consideration.

Causes of Sparking.—Whenever a circuit in which a current is flowing is suddenly parted, a spark is observed, particularly if that circuit contains an electromagnet or any coils of wire surrounding an iron core. The reason of the spark at break of circuit is as follows:—We know that every electric current possesses a property sometimes called "electric inertia," sometimes called "self-induction," by virtue of which it tends to go on. Just as a fly-wheel once set in motion tends to go on spinning, so a current circulating round a coil tends to go on circulating, even though the connexion with the source be cut off. True, the current lasts in most cases only for a small fraction of a second, but it *tends* to go on. It is also known that this quasi-inertia is connected with its magnetic properties, and that it is in the current's own magnetic field that this inertia of self-induction resides.

A current circulating round an iron core has a much greater electric inertia (or self-induction), because it has a more intense magnetic field, than one without an iron core. It requires an expenditure of energy to *start* a current because of this property; and that energy may be considerable. The electric current circulating in a coil possesses energy, and if we stop it by opening the circuit, that energy will show itself by a spark, the spark of the so-called (but mis-named) "extra-current." If we short-circuit the coil, its current—unless there is an electromotive-force to keep it up—will be stopped in a fraction of a second by the internal quasi-friction which we commonly call the "resistance" of the wire.

Now in the armature, when at work, half the current flows —in the standard case we have chosen for consideration—up the coils on the left-hand half of the ring, and the other half of the current flows also up the coils on the right-hand half. If the positive brush is at or near the top, as in Fig. 68, the current flows from left to right through the sections X and W on the left of the brush, and from right to left through the sections T and U on the right of the brush. Now as the armature turns the bars of the commutator come successively into contact with the brush. In Fig. 68 the bars *c* and *d* have already passed the brush; *e* is just leaving it, and *f* is just beginning to pass under it. For a brief moment the brush rests on two adjacent bars *e* and *f*, and thus short-circuits the section V for an instant. The duration will obviously depend on the speed of rotation, on the breadth of the insulating gap between the commutator bars, and on the breadth of the contact-surface of the brush. Now the section V a moment previously belonged to the left-hand half of the ring, and when it has passed the brush, that is to say, when *e* ceases to touch the brush, it will belong to the right-hand half of the ring. It is clear then that in the act of passing the brush the current that was flowing in the section V will be stopped and then started again in the opposite direction through its coils. Every section of the armature as it passes the brush will similarly be transferred from one half of the ring to the other, and will have its current reversed. This is in fact the act of commutation. Now suppose it were arranged that the act of commutation should occur exactly at the point when the coils of the section are not cutting any magnetic lines whatsoever: so that while the coil is short-circuited it shall not be the seat of any induced electromotive-force. Then the current in it will die out, and as it emerges from under the brush it will be thrown as a perfectly idle coil upon the right-hand half of the ring, in which a current is flowing toward the brush. Just before the bar *e* parts company from

FIG. 68.



THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A GENERATOR.

the brush, the current coming up through T and U is flowing through *e* to the brush: but as *e* moves away this current has suddenly to go also round the coils of V. But the current cannot instantly rise to its full strength in the idle coil V, hence before V really gets to work, the current sparks across between *e* and the brush. We have here supposed V to be a perfectly idle coil: now suppose that it is not idle but is actually still cutting magnetic lines, as would be the case if the brush instead of being shifted forward to the neutral line *n n'* had been further to the left. Then it is clear that during the moment of short-circuiting there will be an electromotive-force acting in the coil as it passes the brush. Such an electromotive-force, even though small, may produce momentarily a large current, because the short-circuited resistance is so small. Hence the sparking will be worse than if the coil were absolutely idle.

Now suppose that the brush is shifted just so far the other way, in the direction of the rotation,[1] that as the coil passes the brush it is beginning to enter the fringe of the magnetic field on the right. In that case it will be beginning to cut the magnetic lines in such a way as to tend to set up a current in the reverse direction through it. The ideal arrangement is attained if the brushes be shifted just so far beyond the point of maximum electromotive-force that while the sections pass under the brush and are short-circuited they should actually have a small reverse electromotive-force induced in them; and this action should last just so long in each successive section as to stop the current that was circulating, and start a current in an opposite direction and let it grow exactly equal in strength to that which is circulating in the other half of the armature, which it is then ready to join. If this set of conditions could be attained there should be *no sparks*. A magnetic field of precisely the proper intensity to cause reversal in the commuted section of the armature can usually be found just outside the tip of the pole-piece, for here the fringe of magnetic lines presents a density which increases very rapidly. Since a more intense field is needed to reverse large currents than is required for small ones, it follows that the angle of lead that must be given to the brushes will be slightly greater for large currents than for small ones.

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[1] In the case of a motor, which is separately considered in Chap. XX., the brushes must be shifted in the *opposite* direction to the rotation; *i.e.* there must be a negative lead.

If the brushes are not rocked sufficiently far forward as to touch at the neutral points, there will be free sparking. If they are shifted beyond the neutral points, the sparking is in general less. That is to say there is usually much sparking when the lead is too little; a little sparking when the lead is too great; and no sparking when the lead is right. When the lead is greater than is necessary there is a waste of energy due to the generation in the short-circuited coil of a larger reverse current than is necessary. Moreover, as the lead is increased beyond the neutral point, all the coils that lie in the region between the neutral point and the diameter of commutation are exerting counter electromotive-forces, and the potential at the brushes falls from its maximum.

If in a badly-designed dynamo the armature current circulation in any section is very great, and the field-magnet very weak, it may happen that no position can be found[1] for the brushes in which the intensity of the field is sufficient to reverse the current in the section. Such a dynamo will spark incurably. It is evident that sparklessness will be promoted (1) by dividing up the armature into many sections, so that the reversals of the currents may be done in detail; (2) by making the field-magnet a relatively powerful one; (3) by so shaping the pole-surfaces as to give a suitable fringe of magnetic field of graduated intensity; (4) by choosing brushes of suitable thickness, and keeping their contact-surfaces well trimmed. (See also Chapter XVI.)

Beside the cause of ordinary sparking explained above there are some causes of an exceptional nature. In those dynamos (chiefly those used in arc-lighting) that are constructed to work at high potentials approaching or exceeding 1000 volts there sometimes occurs a phenomenon known as "flashing-over." A long blue spark will on a sudden alteration of the resistance of the circuit be drawn out around the circumference of the commutator from brush to brush. This spark, which is more of the nature of an arc, does little harm in the case of those dynamos which are constructed with commutators of few parts separated by air-gaps, but is very harmful in the case of dynamos having commutators of the ordinary sort with thin mica insulation between the bars; for these are easily short-circuited by the flash-over.

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[1] I have seen a dynamo in which the armature overpowered the field-magnets. When the brushes had a small lead there was a good electromotive-force, but it sparked excessively. With a large lead of nearly 90° the sparks disappeared, but the electromotive-force also vanished!

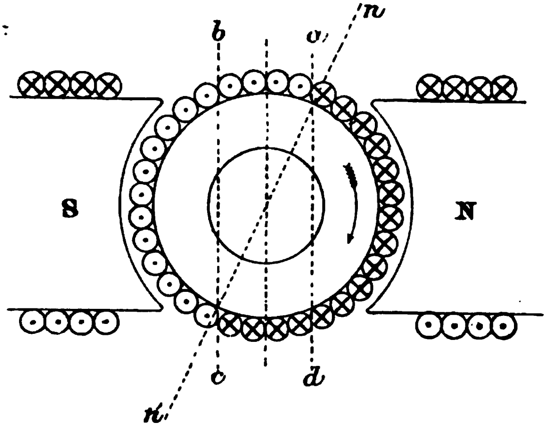
Another cause of sparking is want of symmetry in the winding of the armature: some of the older forms of the Siemens armature were defective in this respect. If the coils of one half of the armature are either more numerous or *nearer to the iron core*, on the average, than those of the other half, the two induced electromotive-forces in the two halves of the armature will be unequal, and, consequently, at every revolution, the neutral points will shift first forward, then backward, giving rise to sparks. Jumping of the brushes when the collector is untrue, or when the brush-holders are defective, is another prolific cause of sparking.

Formerly the fact that a lead must be given to the brushes was ascribed to a sluggishness in the demagnetization of the iron of the armature, and even now some authorities take the view that part of the displacement of the magnetism in the armature is due to the sluggishness of demagnetization of the iron. On the other hand no experimental proof has ever yet been given that the displacement is due to a true magnetic lag. Ewing has shown (see p. 165) that there is a *slow* creeping up of magnetism under the influence of protracted magnetizing forces: but such "viscous hysteresis" will not account for the necessity of giving a lead to the brushes. The apparent magnetic sluggishness of thick masses of iron is demonstrably due to internal induced currents; and for this very reason no one uses solid iron in armature cores. Neither has it been shown that thin iron plates or wires, such as are used in armature cores, are slower in demagnetizing than magnetizing.

Indeed, the reverse is probably true; and, until further experimental evidence is forthcoming, it will be assumed that the alleged magnetic lag is negligibly small in its effects. For further discussion of this, see some experiments which were described in Appendix V. of the third edition of this work. The generation of eddy-currents in any part of the revolving armature will necessarily be accompanied by a demagnetizing action, and will also affect the lead.

Demagnetising Action of Armature.—If in a dynamo there is a forward lead given to the brushes for the purpose of stopping the sparking, there at once results another reaction, namely the production of an actual demagnetizing force or "back-induction." That the armature current does so act is readily demonstrated by considering Fig. 69. Here the field-magnet and armature are represented as before, but the brushes have been given a forward or positive lead; the neutral line *n n'* lying obliquely. The currents are flowing toward the observer in the armature conductors on the left of the neutral line, and from the observer in those on the right of that line. Now let the two lines *a b*, and *c d*, be drawn squarely across the armature through the points of commuta-

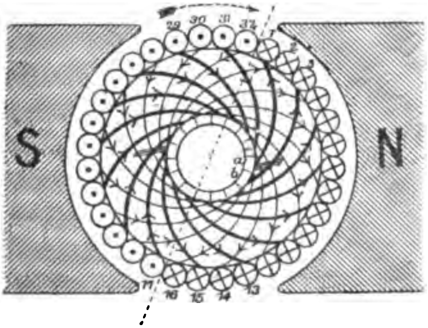
FIG. 69.



DEMAGNETIZING ACTION OF ARMATURE CURRENT OF GENERATOR.

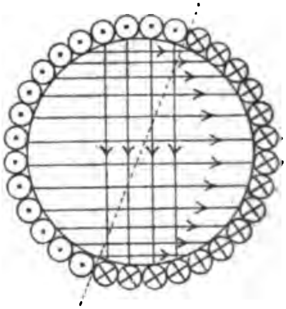
tion corresponding to the two brushes. These lines intersect the outline of the armature in four points. In the diagram there are thirty-two conductors spaced out around the core disk of the armature; and as this armature is drum-wound the end connexions of the conductors will probably be somewhat like those shown in Fig. 70, where each conductor is connected across the end by a double-curved connector to the conductor that is next to the one diametrically opposite.[1] Now so far as any magnetizing actions are concerned it does not matter what the end connexions are, provided they are compatible with the flow of current indicated above in Fig. 69,

FIG. 70.



ACTUAL CONNEXIONS AT END OF DRUM-WINDINGS.

FIG. 71.



CONDUCTORS GROUPED INTO CROSS-MAGNETIZING AND DE-MAGNETIZING BELTS.

with current advancing along the sixteen conductors on the left of *n n'* and retreating along the sixteen on the right of *n n'*. Hence we may consider them, temporarily, as grouped in any way that will assist us to understand their action. Suppose then that the four conductors from 29 to 32 are joined across the ends[2] to the four from 13 to 16; and let the twelve conductors from 1 to 12 be joined across to the twelve from 17 to 28. Our armature windings are now distributed into two belts, one horizontal belt of twelve windings which tends simply to *cross-magnetize*, and one vertical belt of four windings which tends simply to *demagnetize;* for it will be seen that the direction of the circulation around the vertical belt is opposite to the direction of the circulation of current in the magnetizing windings. The breadth of the belt of demagnetizing windings is obviously proportional to the angle of lead, since it subtends double that angle. If the armature in question were carrying 100 amperes then, since there are two paths through the armature circuit (p. 64) each conductor must carry 50 amperes. Hence the number of ampere-turns of cross-magnetizing force is $50 \times 12 = 600$; and the number of ampere-turns of demagnetizing force is $50 \times 4 = 200$.

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[1] For modes of connecting drum-windings, see Chapter XIII.

[2] See Swinburne in *Journal Soc. Teleg. Engineers*, xv. 542, 1886.

Now the cross-magnetizing action which, as we have seen, distorts the field, does of itself slightly diminish the flux of magnetic lines that crosses the armature core from side to side, because in the oblique resultant direction of the magnetization the increased flux tends to produce greater saturation. For other researches on the effect of a cross-magnetism in diminishing the magnetism of the core, see papers by Siemens[1] and Schültze[2] in *Wiedemann's Annalen*. Schültze, in the course of twenty-four experiments, found that the cross-magnetization of an iron core always diminished the longitudinal magnetization. The most recent experiments on these effects are those of Kennelly.[3]

Frölich, in certain experiments with an old-type Siemens dynamo, found that the reaction of the armature current diminished the effective magnetism of the field-magnets nearly 25 per cent. In a more recent research Strömberg,[4] using a Schuckert dynamo, measured the demagnetizing effect of the armature current, and expressed it as being equivalent to a certain number of negative ampere-turns. When the exciting power of the current in the field-magnet coils was maintained at 6250 ampere-turns, the demagnetizing effect of the armature current was as follows:—

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[1] Werner Siemens. *Wiedemann's Annalen*, xiv. 634, 1882.

[2] Schültze. *Wied. Ann.*, xxiv. 663, 1885. See also Oberbeck, Habiliations-Schrift, 1878.

[3] *Electrician*, xxv. 111, 1890.

[4] *Centralblatt für Elektrotechnik*, p. 283, 1887.

Armature Current.	*Equivalent Negative Ampere-turns.*
7·4	650
12·0	850
25·4	1450
44·0	2450
60·4	3650

With stronger constant excitation of the field-magnets the demagnetizing effect of the armature currents was greater. With 13,400 ampere-turns, the demagnetizing effect of sixty amperes in the armature was equivalent to 4400 ampere-turns. With 25,200 ampere-turns the demagnetizing effect of only 30·5 amperes was equivalent to 3100 ampere-turns. This unexpected effect may probably arise from the iron of the field-magnet arriving earlier at a higher stage of saturation than the armature core. It may also have been dependent on the positions of the brushes, which is not specified by Strömberg. In a Manchester dynamo, tested by Prof. Ayrton,[1] 5846 ampere-turns of magnetizing power were needed when no lamps were on, and 10,000 when the machine was furnishing its full output of current: of the additional 4154 ampere-turns, 1754 were needed to compensate for the lost volts (due to internal resistance and lessened permeability) and 2400 to compensate for the demagnetizing effect of the armature current with the increased lead needed to prevent sparking. The greater the lead given to the brushes in a dynamo used as a generator, the greater is the demagnetizing effect of the armature current. In motors, since for a right-handed rotation in a right-handed field, the direction of the armature current is opposite to that in the dynamo, a negative or backward lead has to be given to the brush to avoid sparking—and this backward lead also results in a demagnetizing tendency. If a negative lead (*i.e.* a displacement from the neutral line in the opposite direction to the sense of the rotation) is given to the brushes of a generator, the magnetizing effect of the armature currents will tend to assist the magnetization of the core. Drs. J. and E. Hopkinson[2] have even shown that with a backward lead a dynamo can excite itself by means of the armature currents only; but in such cases of negative lead there is a destructive amount of sparking. The demagnetizing effect is of course proportional to the number of effective ampere-turns of the armature circuit that surround the magnetic circuit, and therefore to the actual number of ampere-turns included, as we have seen, in a belt of double the angular breadth of the angle of lead.[1] Several expedients have been proposed to compensate the cross-magnetizing tendency of the armature currents, and so obviate the variations of lead. In one due to Mather,[2] a small bar electromagnet excited by the armature current is placed perpendicularly between the pole-pieces. Swinburne[3] has discussed the advantages of various similar arrangements for this purpose. Professor E. Thomson proposes to place a series coil on a movable frame over the armature and tilt it till it brings back the neutral point.

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[1] *Journal Inst. Electrical Engineers*, xix. 175, 1890.

[2] *Phil. Trans.*, 1886, part i. p. 347.

In relation to the interference of the armature with the magnetization of field-magnets, it may be pointed out that the "characteristic" curves of dynamo machines (see Chap. X.), which are used to show the rise of the electromotive-force of the machine in relation to the corresponding strength of the current, are sometimes assumed, though not quite rightly, to represent the rise of magnetization of the field-magnets. They represent rather the magnetization through the armature. Now, though the magnetization of an electromagnet may attain to practical saturation, it does not, under a still more powerful current, show a diminished magnetization. But the characteristics of nearly all series-wound dynamos show—at least for high speeds—a decided tendency to turn down after attaining a maximum; and in some machines, for example the older form of Brush with cast-iron ring (see Fig. 157), this reaction is very marked. The electromotive-force diminishes, but the magnetism of the field-magnets does not. An explanation of this dip in the characteristic was put forward by Dr. Hopkinson, in his lecture on "Electric Lighting," before the Institution of Civil Engineers, April 1883, attributing this to the reaction of self-induction and mutual induction between the sections of the armature. No doubt this cause contributes to the effect, as all such reactions diminish the effective electromotive-force. Part of the effect is due to the distortion of the magnetism, but most to the demagnetizing effect as the lead of the brushes is increased. It is at least significant that in the older form of Brush machine, where the reduction of electromotive-force is very great, there is also such a mass of iron in the armature, and so variable a lead at the brushes. Machines with descending characteristics are preferred for arc lighting.

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[1] According to Peukert, who, however, does not specify the angle of lead, the demagnetizing effect of the armature current is proportional to the 1·3 power of the armature current. See *Centralblatt für Elektrotechnik*, ix. 484, 1887.

[2] See *La Lumière Électrique*, xix. 404, 1885.

[3] *Journal Inst. Electrical Engineers*, xix. 105, 1890.

The question of lead of brushes, sparking, and field necessary to reverse the current in a section is further considered in Chapter XVI. in relation to the design of dynamos and the load (or ampere-turns) which an armature can carry.

Spurious Resistance.—There is yet another effect which results from the existence of self-induction in the coils of the armature. In each section the current tends to go on, and in fact does actually go on for a brief time after the brush has been reached. Then the energy of the current in that section is wasted in heating the copper wire during the interval when it is short-circuited; and as it passes on, energy must again be spent in starting a current in it in the inverse direction. All these reactions are of course detrimental to the output of current by the dynamo: especially the loss in short-circuiting. It has been shown by M. Joubert[1] that the loss of energy due to the reversals of the current in the sections of a ring armature is equal to $\frac{n \mathrm{L} i_a^2}{4}$ per second, where n is the number of revolutions per second, L the coefficient of self-induction for the entire ring, and i_a the armature current. Professors Ayrton and Perry have very aptly pointed out[1] that the matter may be conveniently expressed in another way. Since the energy per second conveyed by a current running through a resistance r is equal to $r i^2$, it is evident that the energy lost per second by self-induction is the same as if there were an additional resistance[2] in the armature of the value $r = \frac{n \mathrm{L}}{4}$. There is, therefore, in a rotating armature, an *apparent* increase of resistance proportional to the speed, and this apparent increase, due to self-induction, cannot be got rid of by subdividing the armature into a larger number of sections. It can be diminished in degree by using in the armature more iron and fewer turns of wire, in other words by diminishing the magnetic moment of the coil while giving the field-magnet an increased advantage. The existence of an apparent resistance varying with the speed was first pointed out by M. Cabanellas.[3]

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[1] *Comptes Rendus*, June 23, 1880, January 9, 1882, March 5, 1883; and *L'Électricien*, April 1883. The proof of the above expression is simple. Electric work per second is expressed as product of volts and current. If N magnetic lines are cut n times per second, the average rate is n N. If a ring circuit has coefficient of self-induction L, then current $\frac{1}{2} i_a$ on being sent through that circuit will create $\frac{1}{2}$ L i_a lines of force. Hence the current $\frac{1}{2} i_a$ is virtually caused n times per second to cut across $\frac{1}{2}$ L i_a lines of force; or the work done in stopping the half-armature current in all the sections one after the other for a second of time is $\frac{1}{4} n \mathrm{L} i_a^2$.

Eddy-Currents.—There are two other inductive reactions in the armature to be considered. If any of the framework or metal supports that carry the armature constitute closed circuits which can çut the magnetic lines, they will be the seat of wasteful currents, which will eddy round in them, heating them and absorbing power. In the iron of the armature cores, if not properly laminated, internal eddy-currents (the so-called "Foucault currents") may be set up, absorbing energy and producing detrimental heat; and such currents will also be produced within the conductors which form the coil of the armature, if these are massive as in the "bar-armatures" used for machines that have a large output of current. Frölich, in 1880,[1] pointed out the effect of the presence of these currents; and to them he attributed not only the otherwise unexplained deficit in the work transmitted electrically by a generator to a motor, but also the diminution in the effective magnetism (discussed above as a result of cross-magnetism, and found by Frölich to amount to 25 per cent. of the whole magnetism) observed with great currents and high speeds; and further he attributed to this cause the apparent increase in the number of "dead-turns"[2] at high speeds. Doubtless such currents exist, and the energy they waste will be nearly proportional to the square of the speed:[3] but they may be indefinitely diminished by proper lamination, insulation, and disposition of the structures of the armature.

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[1] *Journal. Soc. Teleg. Eng. and Electr.*, xii. No. 49, 1883.

[2] The value here assigned depends on the assumption that during the moment of short-circuiting the current in the section simply dies out. If it is stopped and reversed by the introduction of a counter electromotive-force, as it ought to be, the value will be less.

[3] *Comptes Rendus*, January 9, 1882, and Nov. 24, 1884; see also Picou, *Manuel d'Électrometrie*, p. 123; and Lodge in *Electrician*, July 31, 1885.

Lamination.—The rules for the proper lamination of structure are different in the different parts; for in the armature core it is desired to cut off all circulation of current that might be induced parallel to the armature conductors; and in the armature conductors it is desired to cut off all flow of current from one side or edge of the conductor to the other. The planes of lamination must of course be arranged to cut right across the direction in which the parasitic current might otherwise flow. Now since (see p. 22) the direction of the induced electromotive-force, the direction of the motion, and the direction of the magnetic lines are all three at right angles to one another, it suffices in each case to describe the plane of lamination, by stating to which of these three directions it must be normal. It will then contain, or be parallel to, the other two directions.

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[1] Berlin Academy, *Berichte*, Nov. 18, 1880; and *Elektrotechnische Zeitschrift*, ii. 174, May 1881; also vol. ix., Nov. and Dec., 1888.

[2] Meaning the number of revolutions by which the actual speed exceeds the number needed, in the absence of all reactions, to produce the electromotive-force.

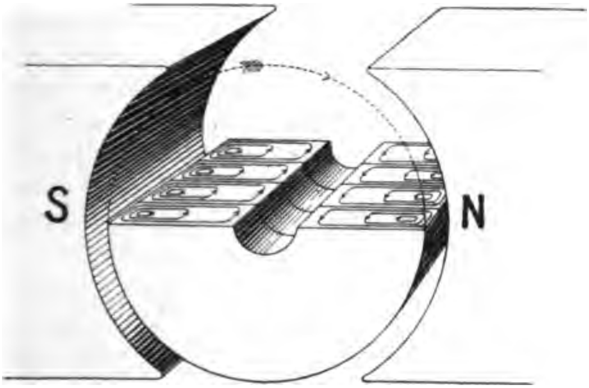
[3] Clausius has introduced terms into his equations (*Wied. Ann.*, xx. 354, 1883; and *Phil. Mag.*, series 5, xvii. 46 and 119, 1883) to include the effects of the eddy-currents. They have also been theoretically treated by H. Lorberg (*Wied. Ann.*, xx. p. 389, 1887).

Direction of	Direction of Lamination Planes.		
	In Armature Cores.	In Armature Conductors.	In Polar Masses.
Motion	parallel	normal	parallel
Magnetic Lines	parallel	parallel	parallel
Induced Electromotive-force	normal	parallel	normal

It will be noticed that the lamination for the polar masses is the same as for the core; so that the polar masses are virtually continuations of the core-disks.

The necessity for dividing the cores of drum armatures and of ring armatures (if cylindrical, not discoidal) into core-disks, may be illustrated as follows:—In any conductor rising in the left-hand gap-space there will be generated an electromotive-force tending from back to front. Hence if the core were of solid iron, a current would flow forwards along the outer part of the core on the left, and back along the outer surface on the right. Division of the core into disks will obviously minimise such currents. It will not, however, entirely eliminate them, for as Fig. 72 shows in the sectional view of the core-disks, it is possible for eddy-currents to flow in the substance of these. As a matter of

FIG. 72.



EDDY-CURRENTS IN CORE-DISKS.

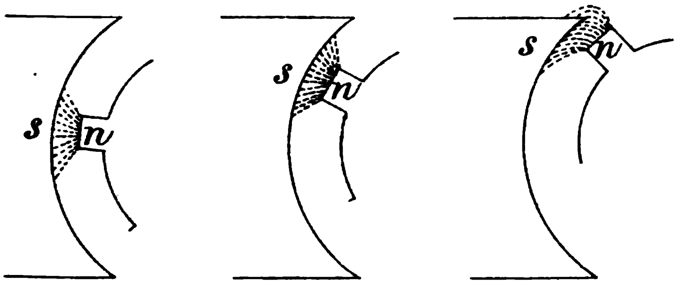
fact it is found that if they are too thick, or are not properly insulated from one another, they heat: and the heating is mainly at the outer surface, where the eddies are strongest. As a general rule it may be said that core-disks should not exceed 2 millimetres in thickness. The same thickness is suitable for the ribbon cores of discoidal rings. The new laminated armature of the Brush arc-light machine, Fig. 303, p. 462, when used in place of the old solid armature, Fig. 302, was found to diminish greatly the number of "dead turns," besides saving much energy previously lost in heating.

With ring armatures that have an internal field (see p. 76) similar eddies will be set up in the driving spindle and in the metal arms that support the core; wasting power and heating them.

If there is a stray magnetic field leaking from the flanks of the polar masses into the flat surface of the end-discs of the core, eddy-currents will also be set up in the latter. This can be obviated by making the total axial length of the armature core rather greater than the length of the polar masses parallel to the axis.

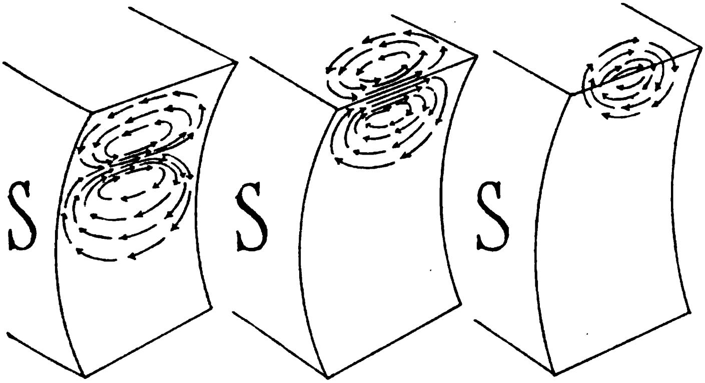
Eddy-currents in Pole-pieces.—If the masses of iron in the armature are so disposed that as it rotates, the distribution of the lines of force in the narrow field between the armature and the pole-piece is being continually altered, then, even though the total amount of magnetism of the field-magnet remains unchanged, eddy-currents will be set up in the pole-piece and will heat it. This is shown by Figs. 73 to 78, which represent the effect of a projecting tooth, such as that of a Pacinotti ring, in changing the distribution of the magnetism of the pole-piece. Figs. 76 and 77 (corresponding respectively to Figs. 74 and 75) show the eddy-currents, grouped in pairs of vortices. The strongest current flows between the vortices and is situated just below the projecting tooth, where the magnetism is most intense; it moves onward following the tooth. Fig. 78 shows what occurs during the final retreat of the tooth from the pole-piece. These eddy-currents penetrate into the interior of the iron, although to no great depth. Clearly the greatest amount of such eddy-currents will be generated at that part of the pole-piece where the magnetic perturbations are greatest and most sudden. A glance at Figs. 63, 67, 77, and 78 will at once tell us that this should be at the "leading" corner or "horn" of the pole-piece of the

FIG. 73. FIG. 74. FIG. 75.



ALTERATION OF MAGNETIC FIELD DUE TO MOVEMENT OF MASS OF IRON IN ARMATURE.

FIG. 76. FIG. 77. FIG. 78.

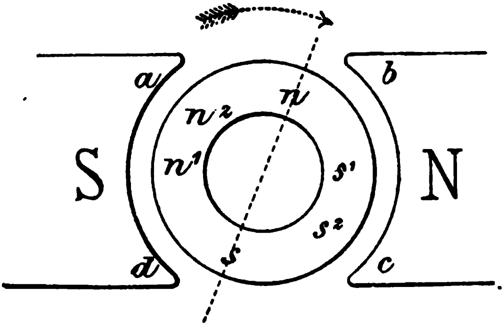


EDDY-CURRENTS INDUCED IN POLE-PIECES BY MOVEMENT OF MASSES OF IRON.

generating dynamo. As a matter of fact, when any dynamo which has horned pole-pieces (such as the Gramme) has been running for some time as a generator this is found to be the case. The "leading" horns *a* and *c*, of Fig. 79, are found to be hot, whilst the "trailing" horns *b* and *d* are found to be comparatively cool. When the dynamo is used as a motor, the reverse is found to be the case: the "leading" horns *a* and *c* are cool, the "trailing" horns *b* and *d* are hot. A reference to the magnetic field of the motor, as drawn in Chap. XX., will explain the latter case.

Closely connected with this effect is another, first pointed out to the author by M. Cabanellas. A Gramme magneto machine with permanent magnets is observed to lose power during its use as a motor; the field-magnets decrease in strength. If, then, it is used as a generator, the field-magnets regain their magnetism. The effect is explicable[1] when the

FIG. 79.



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[1] The following explanation was given by the author at the International Conference of Electricians at Philadelphia, 1884 (see report in *Electrical Review*, Dec. 13, 1884). "To explain these facts, and their mutual relation, I must relate one other observation which I have made, and which connects both sets of facts. . . . . Suppose you take a horse-shoe magnet, having the usual armature or 'keeper' of iron. You can purchase such an instrument of any optician, who will probably give you instructions never to pull the armature off suddenly for fear you injure the magnetism. He could not possibly give you worse directions. Take such a magnet and try what the effect really is. Fasten it down upon a board with brass screws, and fix a magnetometer near it—a common compass will answer—and notice how much the magnet pulls the needle round. Then put on the armature, by placing it at the bend of the magnet; draw it slowly to its usual position, and suddenly drag it off. You will find that by this action your magnet will have grown stronger. Do this twenty times, and you will make it considerably stronger. I have made a magnet 1·2 per cent. stronger by putting on the armature very gently and pulling it off suddenly. If you reverse the operation, by letting the armature slam suddenly against the poles and then detaching it gently, you will find that the magnetism will go down. I have made magnets lose 1·3 to 2·1 per cent. in this way. Why does this occur? How does

magnetizing effect of the eddy-currents is taken into consideration.

Effects of Mutual Induction.—Some forms of armature are peculiarly defective in the matter of being so constructed as to allow of much induction between neighbouring sections or parts of the coil, causing the rise of the current in one section to exert an opposing induction on a neighbouring section, and thereby, though not necessarily wasting any energy, making the machine act as if it were a smaller machine. The Bürgin armature, which had six or eight rings side by side on one spindle, suffered from induction between each section, and those belonging to the rings on the right and left of it; and it was only by a careful alternation of positions that this defect was mitigated. In disk armatures of the Niaudet and Wallace-Farmer type each of the parallel coils acted inductively on its neighbour. Beyond doubt the armature with least of this defect is the drum armature. Clausius has shown[1] that after a section has been short-

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it explain the two phenomena noticed just now? If you suddenly take away a piece of iron from a magnet, you do work against the magnetic attraction, and the induced currents which are set up in the iron or steel of the magnet are always (as we know from Lenz's Law) in such a direction as to oppose the motion; that is to say, they are in such a direction as will make the magnet pull more strongly than before. By suddenly detaching the armature, we magnetise the magnet more strongly than before, by means of currents circulating within its own mass and within the mass of the armature. In the reverse motion, when you allow the armature to slam up, there are induced currents which are in such a direction as to oppose the motion of slamming; they, therefore, decrease the magnetism of the magnet. Apply this to the dynamo and to the motor. You magnetize more highly by pulling off the armature. That is precisely what is occurring in the field when the machine is being used as a generator. You are dragging away the armature from the active horn *a* of the pole-piece, and the effect is to generate induced currents in that horn. It therefore gets hot. So does the other leading horn *c*, for the very same reason. In the case of the motor the horns *b* and *d* are the active ones, and the armature is being continually dragged up toward them, and they get hot from internally induced currents. It is for this reason that in my Cantor Lectures I recommended that pole-pieces should always be laminated. The presence of these induced currents explains the heating effect, and it also explains how it is that when a magneto machine is used as a motor the magnet is weakened, and when used as a generator the magnet is strengthened."

[1] *Wiedemann's Annalen*, Nov. and Dec. 1883; and *Phil. Mag.*, Jan. and Feb. 1884.

circuited on passing a brush, it exercises a deleterious inductive effect on the neighbouring coil in advance of it, and that this effect is proportional to the number of turns in the section. It can, therefore, be diminished by increasing the number of sections, thereby diminishing the number of turns of wire in any one section of the armature.

Mutual induction between adjacent parts is of enormous importance in alternate-current machines; and indeed everywhere, throughout dynamos in general.

Lag due to Self-Induction.—This electric inertia of the current which circulates in the sections affects slightly the lead that must be given to the brushes, and it also reacts on the neighbouring coils. If a coil is short-circuited too early, before it reaches the neutral point, the sudden rush of its own current round itself tends by mutual induction to stop the current in the coil behind it, and to accelerate the inverse current in the coil in front of it. These actions are diminished by increasing the number of sections and making the individual sections consequently smaller. The induction even extends to the iron of the cores. In every particle of the iron at the moment when it arrives at the position where its magnetism must be reversed, an internal current is set up which retards the reversal of the magnetism and makes it *apparently* lag in its magnetization, as well as grow hot. This effect can also be diminished by properly laminating the core and arranging it so that its magnetism is reversed gradually instead of suddenly.

Remedy for Induction Troubles.—The one important way of diminishing these deleterious reactions is happily a very simple one. It is clear that the demagnetizing effect is due to the lead of the brushes, and this again is due to the cross-magnetizing action. This therefore must be compensated or reduced to a minimum by some means. It has been shown that the electromotive-force of the dynamo is proportional to three things, the number n of revolutions per second, the total number N of magnetic lines in the effective field, and the number C of conductors around the armature. Now, for a given size of armature, the inductive reactions are proportional to C. If we can decrease C while increasing either of the other terms, we may thereby decrease the deleterious reactions and yet keep the same electromotive-force as before. Now it is inconvenient to increase the speed, and moreover some of the deleterious reactions, mechanical (such as friction) as well as electrical, increase when the speed increases. The only way then is to increase N, the number of magnetic lines in the effective magnetic field. This can be done by having enormously strong field-magnets which will entirely overmaster the armature. If the field-magnets are large, and of wrought iron, and if there is plenty of iron in the armature core, then, without increasing the speed, we may get the same electromotive-force while using fewer turns of wire on the armature. The ideal dynamo of the future for constant pressure work will have but one turn of wire to each section. It will have practically no lead at the brushes, will not spark, and its internal resistance will be practically *nil*.

It is also important to observe that distortion of the magnetic field and some of the resulting troubles can be partially obviated by so shaping the polar surfaces that they come nearer to the armature at the region at right angles to the diameter of commutation; the pole-pieces being cut away so as to give a wider clearance at the outer edges. It is obviously possible by proper shaping to produce concentration of the magnetic lines at any desired region of the magnetic field. Ryan[1] has made a special study of the relation between the polar shape, the breadth of the gap-space, and the resulting curve of induced electromotive-force.

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[1] *Amer. Inst. Electrical Engineers*, Sept. 22, 1891.

CHAPTER V.

MECHANICAL ACTIONS AND REACTIONS IN THE ARMATURE.

WHENEVER a conductor carrying an electric current lies in a magnetic field across the direction of the magnetic lines, it experiences a mechanical force. This force always tends to drag the conductor sideways out of the field, and acts in a direction at right angles to the magnetic lines and at right angles to the conductor itself. Rules for remembering the relation between the directions of the magnetic lines, the current, and the resulting force, have been given by various writers. The most convenient rule is that of Fleming, in which the three directions are represented respectively by the fore-finger, the middle-finger, and the thumb of the *left* hand.[1] In a motor it is this drag on the conductors which drives the armature mechanically. In a dynamo the drag acts against the driving power of the steam-engine and opposes the rotation. When a mechanical engineer first considers a dynamo he is often puzzled to understand what there is in it that necessitates so much driving power. He sees the armature revolving with ample clearance between the polar faces of the field-magnet. The friction of the bearings does not absorb more than a minute fraction of the horse-power delivered by the engine. He sees the brushes pressing against the copper commutator, but knows that their friction is also a negligible quantity; moreover he is soon informed that friction has nothing to do with the operation of the machine. Where does the power go to? What is it that requires such a force to be continually exerted to keep up the rotation? The answer is, that there is a continual drag of the invisible magnetic lines on the conductors through which the current is flowing: that the generation of the current depends on the conductors being forced across the field that drags at it. In every form of apparatus generating currents by magneto-electric induction, the currents generated produce a mechanical reaction tending to stop the very motion that generates them.

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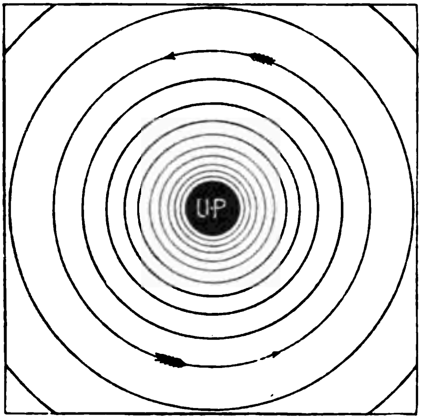
[1] Contrast with p. 23, where, for the current generated in a *dynamo* the *right* hand is used. Remember that in a dynamo the direction of the current agrees with that of the induced electromotive-force, whereas in a motor the current flows against the induced electromotive-force. Further, in the dynamo the mechanical drag acts against the direction of motion, whereas in a motor the drag produces the motion in the same direction as itself. Hence the use of *right* hand for dynamo, *left* hand for motor, to give the relation between magnetism, current, and motion.

The drag of a magnetic field upon a conductor that carries a current may be considered from the magnetic point of view. As pointed out on p. 26, above, such a conductor is surrounded by a whirl of magnetic lines. Around a long straight conducting wire not placed in any magnetic field, these magnetic lines form a system of concentric circles (see Fig. 13, p. 27) which are close together near the conductor, and wider apart at a distance away, resembling Fig. 80 in general disposition.

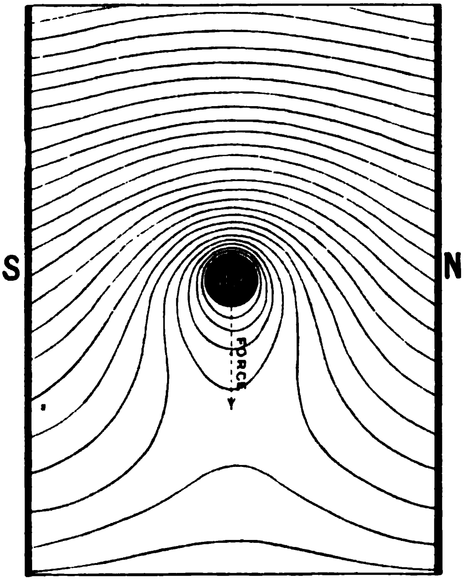
FIG. 80.



MAGNETIC FIELD OF A STRAIGHT CONDUCTOR CARRYING A CURRENT.

If the current is coming towards the observer, or *up*, in the figure which shows a cross-section of the conductor, the positive direction along the magnetic lines will be left-handed or counter-clock-wise. If now such a conductor be placed in a uniform magnetic field—one, for example, between a large north magnetic pole on the right and a south magnetic pole on the left, a compound field will be produced, due to the blending of the magnetic lines of the conductor with those of the field. In considering this distorted magnetic field it should be remembered that the mechanical actions that result may always be known by supposing the magnetic lines to act as elastic cords tending to shorten themselves. There is in fact a tension along the magnetic lines and a pressure at right angles to them, both proportional at every point to the square of their density. A mere inspection of the lines of Fig. 81 will accordingly show that there will be a resultant drag upon the conductor in the direction shown by the dotted arrow.

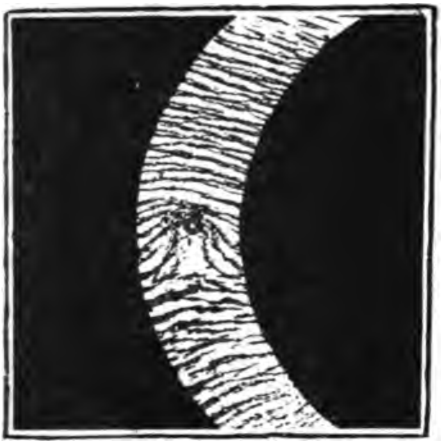
FIG. 81.



MAGNETIC LINES DUE TO CONDUCTOR CARRYING CURRENT PLACED IN MAGNETIC FIELD.

The actual magnetic field produced around a conducting wire in a magnetic gap between two poles, as revealed by iron filings, is shown in Fig. 82.

FIG. 82.



ACTUAL MAGNETIC FIELD AROUND CONDUCTING WIRE IN MAGNETIC GAP.

We may consider Fig. 82 as approximately representing that which goes on in a dynamo, or in a motor, in each of the gap-spaces between the armature core and the adjacent polar face. Each conductor on the armature will be similarly dragged by a force proportional to the intensity of the magnetic field and to the strength of the current.

Torque and Speed.—Engineers recognise that power, being the rate of expending energy or of doing work, can always be expressed as the product of two factors. In the case of rectilinear motion, the power may be expressed as the product of force and speed. For example, if the force pulling along a belt[1] be equal to the weight of 66 pounds, and the belt-speed be 2000 feet per minute, the amount of power it is delivering is 132,000 foot-pounds per minute, or 4 horse-power.

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[1] Or more precisely, the difference between the forces in the tight and slack parts.

But the power may be equally well expressed in terms of angular force (*i. e.* torque) and angular speed ; and these quantities are more convenient in the case of power transmitted along a rotating shaft.

The useful term *torque,* now generally accepted by engineers, was originally suggested by Professor James Thomson, then Professor of Mechanical Engineering in the University of Glasgow. It is the same thing as that which has gone by the names of "turning moment," "moment of couple," "axial couple," "angular force," "axial force," in German by that of "Zugkraft," and in French by those of "effort statique," and "couple mécanique." *Torque* is preferable in many ways to any of the older terms. Just as the Newtonian definition of *force* is that which produces or tends to produce motion (along a line), so *torque* may be defined as that which produces or tends to produce *torsion* (around an axis). It is better to use a term which treats this action as a single definite entity than to use terms like "couple" and "moment," which suggest more complex ideas. The single notion of a twist applied to turn a shaft is better than the more complex notion of applying a linear force (or a pair of forces) with a certain leverage.

For torque we shall use the symbol T. If force f acts with leverage (*i. e.* radius) r, the torque is equal to $f \times r$. If the force is in pounds' weight and radius in feet, the torque will be expressed in pound-feet ; *i. e.* in terms of the number of pounds, which, acting with a leverage of one foot, would produce an equal tendency to turn. If force is given in dynes and radius in centimetres, the torque will be expressed in dyne-centimetres. (See Appendix A, on Units.)

In order to bring—

dyne-centimetres	to	gramme-centimetres,	divide by 981
dyne-centimetres	to	metre-kilogrammes,	divide by 981×10^5
dyne-centimetres	to	pound-feet,	divide by $13{\cdot}56 \times 10^6$
pound-feet	to	metre-kilogrammes,	divide by $7{\cdot}23$

Angular speed is commonly expressed by engineers in terms of the number of revolutions per minute, or, sometimes, of revolutions per second. The scientific mode is to express it in *radians per second.* (The radian is that angle whose arc equals the radius; so that 2π radians equal one revolution or 360°). The symbol for angular speed is ω, so that if n represents the revolutions per second, $\omega = 2\pi n$.

In order to bring:—

revolutions per minute	to	revolutions per second,	divide by 60
revolutions per second	to	radians per second,	multiply by 2π
revolutions per minute	to	radians per second,	divide by 9·55
radians per second	to	revolutions per minute,	multiply by 9·55

We have then the following relations between linear force f, linear speed v, torque T, angular velocity ω, radius r, revolutions per second n, and power w.

$$w = v . f = \frac{v}{r} . fr = \omega \mathrm{T} = 2 \pi n \mathrm{T}.$$

The power w will be expressed in *ergs per second*, if v is given in centimetres per second and f in dynes; or if T is given in dyne-centimetres. If T is in pound-feet, w will be expressed in foot-pounds per second.

In order to bring:—

ergs per second	to	watts,	divide by 10^7
ergs per second	to	kilogramme-metres per second,	divide by $9·81 \times 10^7$
ergs per second	to	foot-pounds per second,	divide by $1·356 \times 10^7$
ergs per second	to	horse-power,	divide by 746×10^7
watts	to	horse-power,	divide by 746
watts	to	chevaux-vapeur,	divide by 736
watts	to	foot-pounds per second,	divide by 1·356
watts	to	kilowatts,	divide by 1000
kilowatts	to	horse-power,	multiply by 1·345

Output of Dynamos and Motors.—A good dynamo will convert over 90 per cent. of the mechanical power supplied to it into electric power. Similarly a good motor will convert over 90 per cent. of the electric power supplied to it into mechanical power. Both mechanical power and electric power may be expressed in terms of the same units, either in *horse-power*, or in *watts*, or in *kilowatts*.

Approximate calculations of the horse-power required for a dynamo of any prescribed output are readily made. Multiplying the number of amperes i of current which the dynamo is to yield, by the number of volts e of pressure at which the current is supplied, gives the output in *watts*. Dividing by 746 gives the corresponding electric horse-power, which will be about 90 per cent. of the mechanical horse-power to be supplied to the shaft of the dynamo.

Example: A dynamo is required to furnish 300 amperes (to light 600 glow lamps) at a pressure of 105 volts. Output is 31,500 watts = 42·2 horse-power (electrical). Therefore allow 46·9, or say 50 (mechanical) horse-power.

In the converse way we may calculate the requisite supply of electric power to a motor.

Example: A motor is required to give an actual output of 5 horse-power. Multiplying by 746, we find it must give out 3730 watts as mechanical power; which will be about 90 per cent. of the electrical power supplied to it. This will therefore need to be about 4144 watts. If the supply is from mains that are at a pressure of 200 volts, the current required will consequently be a little over 21 amperes.

Relation between Torque and Current.—Since the electric power given out by the armature of a dynamo is the product of two factors—volts and amperes—and the mechanical power supplied to it by the rotating shaft is also the product of two factors—speed and torque—it becomes a matter of some interest to ascertain whether there is any direct relation between the factors themselves. Let E stand for the volts generated in the armature, and i_a for the amperes flowing through it. We may then equate the two separate expressions for the number of watts of power supplied to and furnished by that armature as follows :—

$$\text{watts} = \mathrm{E}\, i^a = 2\pi n \mathrm{T} \times 1{\cdot}356;$$

where T is given in pound-feet; n in revolutions per second; E the whole volts generated by the armature; and i_a the whole amperes flowing through the armature. But E is proportional to the speed if the magnetism is constant, the fundamental expression for it being (see pp. 47 and 211), for an ordinary two-pole machine,

$$E = n\,C\,N \div 10^8;$$

where C is the number of conductors around the armature, and N the magnetic flux through its core. Inserting this value for E, and cancelling n from both sides, we get:

$$\frac{C\,N\,i_a}{1 \cdot 356 \times 10^8} = 2\pi T;$$

whence

$$\frac{C\,N\,i_a}{8 \cdot 52 \times 10^8} = T \text{ (in pound-feet).*}$$

From this it appears that if in a given machine the magnetism is constant, the torque depends in no wise upon the speed, but only upon the current flowing through the armature, and on the magnetism.

These expressions apply equally to dynamos and to motors. They show that if it is desired to build slow-speed machines provision must be made for a very large magnetic flux; for only by making N large can the dynamo at slow speed yield the requisite volts, or the motor exert the needful torque.

Drag on Armature Conductors.—We are now in a position to understand that the drag really comes on the armature conductors. In the dynamo it is they that have to be driven, in the motor it is they that drive. We may at once proceed to calculate the amount of such drag. There are three methods of doing this: two being electrical and one a purely mechanical calculation.

METHOD I.—By the last formula the torque is calculated; and from this the total peripheral force is found by dividing by the known radius of the armature. Hence the force per conductor is obtained by dividing by the number of active conductors.

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* If T is desired in metre-kilogrammes, the divisor on the left must be replaced by the value $61 \cdot 5 \times 10^8$.

Example in the Edison-Hopkinson dynamo (p. 413). $i_a = 326$; $C = 80$; $N = 10{,}850{,}000$; radius $= 0{\cdot}458$ ft.; whence $T = 332$ pound-feet, and total peripheral force $= 724{\cdot}7$ pounds. This would give about 9 pounds average force per conductor if all were active; but only about 58 of them are in the magnetic field at one time; hence, the average force per conductor is about 12½ pounds. If the magnetic field in the gap-spaces is not uniform there comes a stronger drag on those conductors which lie in the place where the magnetic lines are densest.

METHOD II.—The drag on a conductor of length l, in a magnetic field of intensity H, carrying current of i amperes, is

$$f\,(\text{dynes}) = i\,l\,\mathsf{H} \div 10.$$

This formula[1] is only applicable if H, the density of the field in the gap-space, is known. If l'' and $\mathsf{H}_{''}$ are given in inch measures (see p. 142), the formula becomes

$$f\,(\text{pounds}) = i\,l''\,\mathsf{H}_{''} \div 11{,}303{,}000.$$

Example, as before: Current in any one conductor will be $\frac{1}{2}\,i_a = 163$ amperes; $l'' = 20''$, and $\mathsf{H}_{''} =$ about 43,300 lines per square inch, the area of the gap-space being about 250 square inches. Whence drag on each conductor $= 12{\cdot}49$ pounds.

METHOD III.—Ascertain actual horse-power on armature; multiply by 33,000 to reduce to foot-pounds per minute, and divide by the peripheral speed (in feet per minute). [The horse-power may be reckoned from the electrical output as on p. 110.] Then divide by the number of active conductors. Or, in symbols,

$$f\,(\text{pounds av. drag per conductor}) = \frac{\text{H.P.} \times 33{,}000}{\text{ft. per min.} \times \text{C.}}.$$

Example, same as before: Since $i_a = 326$, and $E = 108{\cdot}5$ volts, $\text{H.P.} = 326 \times 108{\cdot}5 \div 746 = 47{\cdot}45$. Also periphery $= 2\pi \times$ radius $= 2{\cdot}88$ ft. This, at 750 revs. per minute, gives 2158 ft. per min. as peripheral speed. Assuming fifty-eight conductors to be active, we get

$$\text{av. force on each conductor} = \frac{47{\cdot}45 \times 33000}{2158 \times 58} = 12{\cdot}5 \text{ pounds.}$$

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[1] To give f in kilogrammes, the divisor 10 must be replaced by 9,810,000.

A convenient approximate rule may be given as follows:— If we assume, as a sort of rough average for the magnetic field in the gap-space of a dynamo or motor, the value of 40,000 lines to the square inch, or say 6300 lines per square centimetre, then *the drag per inch of conductor will be* 0·00354 *pound for each ampere of current carried.* In alternate-current dynamos the intensity of the field is seldom more than half as great as this.

Such, then, is the drag that magnetic fields exert upon the armature conductors; and, it must be remembered that the drag is not a steady one. When the conductor emerges from the gap-space, though there is still a current in it, the magnetic drag is taken off. Twice, therefore, in each revolution this drag is suddenly removed and suddenly put on again, increasing the racking action. In the case of alternate-current machines where the relation of phase between the currents and the magnetic fields complicates the matter, the drag is not simply taken off and put on twice in each complete period, but is actually reversed; the armature conductors being driven with a back drag on them, then experience a forward drag and tend to drive, then once more are driven, and again tend to drive as the current reverses. In the alternate current machine acting as generator the intermediate forward drags are slight and of short duration; in the machine acting as motor it is the backward drags that are of short duration.

It must further be remembered that the conductors of the rotating armature are also subject to centrifugal force, and must be strongly held in with external binding-wires to prevent them from flying.

Need of Driving Horns.—It is then obvious that under the mechanical conditions now described there is need of a good positive method of conveying the driving power from the shaft to the conductors on the outside of the armature. In the dynamo it is they, not the core-disks, that need to be driven. In the motor, it is they that drive the shaft. In the design and construction of machines this is a matter of prime importance. The question of construction is complicated by the consideration that whilst the copper conductors must be mechanically connected to the shaft in the most positive way, they must not be metallically connected, but, on the contrary, must be insulated therefrom. Different constructors adopt different modes of accomplishing the end in view. Some makers key on to the shaft a strong hub provided with spokes that project beyond the surface of the core-disks, and, protected by layers of adequate insulation, thus drive the copper conductors. Others secure the core-disks mechanically to the shaft, and insert wedges of wood or of hard fibre into nicks in the periphery to serve as driving horns. In cases where toothed core-disks are used, no other driving horns are necessary, the copper conductors being wound between the teeth. Students of design should carefully examine the practical modes adopted by modern makers described in Chapter XIII.

Curves of Torque.—It was shown above that if the magnetic flux is constant, T was proportional to *i*. But in all cases the current in the armature itself distorts the magnetic field, and, when the brushes are set at a non-sparking point, exerts a demagnetizing action. And, in fact, the magnetism of the machine depends on its mode of winding, whether excited separately, or in series, or in shunt. These matters complicate the relations between T and *i*, and necessitate the use of curves to follow them out.

Frölich has given[1] such curves showing these relations, and has also argued from the law of magnetic saturation that these curves should for small speeds be curved, and for large speeds become nearly straight lines. He has also shown that in a motor the torque is less nearly proportional to the current than in a generator. The following tables summarise the results of his experiments on a series-wound Siemens dynamo used in both functions:—

Generator—

Current	..	2·83	9·56	14·3	19·8	24·3	36·6	amperes.
Torque	..	5·1	10·61	14·8	21·3	29·6	44·0	kilos.

Motor—

Current	..	13·3	21·0	28·1	36·8	amperes.
Torque	..	10	20	30	40	kilos. at circumference.

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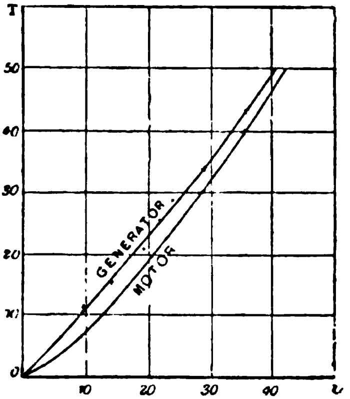
[1] *Elektrotechnische Zeitschrift*, iv. 61, Feb. 1883.

These results are plotted out in Fig. 83 for the two cases. Similar curves have been given by Deprez[1] for the Gramme machine, and by Ayrton and Perry[2] for a De Meritens motor. It can be shown that the torque is proportional to the square root of the heat-waste in the motor or dynamo. As, moreover, the current in a motor cannot be maintained without the continual expenditure of energy equal to $i^2 r$ watts, it follows that the continuous torque in a motor costs a certain expenditure, which will not only vary with the actual load on the motor, but is different in different types of motor. In a badly designed motor with a weak field-magnet, a strong current running through a high internal resistance (and therefore expending much energy as heat) will produce but a feeble torque. For economy it is therefore important to know at what cost in heat the torque is attained. The ratio may be expressed algebraically as

FIG. 83.



CURVES OF TORQUE.

$$\frac{T}{\text{heat-waste}} = \frac{E\,i}{2\pi n i^2 r} = \frac{E}{2\pi n i r};$$

where r is the internal resistance, E the total electromotive-force of the dynamo, and n the number of revolutions per second. It is, however, preferable to measure T by a direct dynamometric process. Marcel Deprez, who has given to this important ratio the rather awkward name of the "price of the statical effort," has also given curves showing the variation of this ratio with the speed at which the machine is run.

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[1] *La Lumière Électrique*, xi. 42, Jan. 5, 1884.

[2] *Journal Soc. Teleg. Eng. and Electricians*, xii. No. 49, May 1883. See also Hummel, *Electrotechnische Zeitschrift*, viii. 427, 1887.

Professors Ayrton and Perry have shown, in their memoir on electromotors, that as the speed increases it requires a greater and greater current through the motor to produce a given torque, probably in consequence of the demagnetizing action of eddy-currents.

A number of *mechanical characteristics,* giving the relations between speed and torque in a number of different cases, will be found in Chapter XX. on Motors.

Stray Power.—In the preceding paragraphs it has been assumed that the mechanical power applied *at the shaft* to drive the armature was equal to the electrical power actually generated in the armature. The power to be applied at the pulley is, however, always greater than this ; for, in the first place, some of the applied power is lost by friction in the bearings, &c., and never reaches the armature. But of that which actually reaches the armature, not all is actually converted into electrical power. There are, beside the friction at the bearings and brushes, three sources of loss, viz.: (1) air-friction, (2) hysteresis, (3) eddy-currents. The first of these is insignificant, except in those cases where curved spokes are employed with the object of making the armature act as a fan, and even then is small. The second is by no means negligible, but seldom adds more than 1 or 2 per cent. to the driving power. The third is the most important of all, especially in large machines. In all the moving metal masses, unless laminated, there will be eddy-currents set up if they cut magnetic lines. Even in the metal of the shaft, power may be lost from this cause if there is leakage of magnetic lines into it. The mode of investigating the separate sources of loss is described in Chapter XXVIII. on the Testing of Dynamos and Motors. Whatever these losses, it is evident that they all call upon the supply of power : for the power supplied is necessarily equal to the sum of the power actually converted in the armature into electric power, and the stray power wasted in the ways enumerated.

Efficiency of Dynamos and Motors.—Efficiency is a term used in several senses, which it is well to distinguish.

(1) *Efficiency of Conversion* or *Gross Efficiency,* is the

relation between the gross electrical power actually converted in the armature, and the gross mechanical power imparted by belt or coupling to the shaft. If 12 per cent. of the gross mechanical power is lost in friction at the bearings, friction at the brushes, air friction, hysteresis, and eddy-currents, then the remaining 88 per cent. being actually converted in the armature, we should describe the efficiency of conversion as 88 per cent.

(2) *Electrical Efficiency*, or *Economic Coefficient*, is the ratio between the nett electric power or nett output of the dynamo, and the gross electric power, or power actually converted in the armature. Thus, if in a shunt dynamo 3 per cent. of the gross electric power is wasted in heating the resistance of the armature, and another 3 per cent. is wasted in maintaining the magnetizing current in the shunt winding, the output or nett electric power will be only 94 per cent. of the gross electric power; or the electrical efficiency is 94 per cent. This ratio depends only on the resistances of the machine. In modern machines it may even attain 97 per cent.

(3) *Commercial Efficiency* or *Nett Efficiency*, is the ratio between the nett electrical output and the gross mechanical power supplied by belt or coupling. It is therefore equal to the product of the efficiency of conversion and the electrical efficiency. In the example given it is 94 per cent. of 88 per cent., or 82·72 per cent.

RELATION OF SIZE TO CAPACITY AND EFFICIENCY.

For years past the author has been the advocate of large dynamos, not because he has any admiration for mere bigness, but because, as in steam-engines, so in dynamos, the larger machines may be made more efficient than the small, in proportion to their cost. There has been a considerable amount of controversy upon the relation that subsists between the linear dimensions of similar machines and their permissible output and their efficiency; the divergence of views arising mainly from difference of opinion as to the assumptions that are suitable at the outset. In the first edition of this work the author laid down the proposition that if the speed of rotation remains the same and the intensity of the magnetic field (per square centimetre) is also maintained unchanged, then the output of a machine n times as great, in all linear dimensions, as any given machine, would be increased in the proportion of n^5, and the coefficient of waste would be in the proportion of n^{-3}. Now though this may be *à priori* true in the abstract, the very assumptions made for the sake of simplification are opposed to actual conditions of working; for it is inexpedient to drive large machines at the same speed as small ones; and to procure equal magnetization with large magnets wastes more energy in proportion, on account of the relatively greater difficulty of getting rid of the waste heat from the magnetizing coils, the energy requisite to be spent on magnetizing being nearly proportional to the volume of iron to be magnetized, and the power of getting rid of the heat being only proportional to the surface. Amongst those who have discussed the problem are Hopkinson, Frölich, Ayrton, Mascart and Joubert, Kapp, Storch, Rechniewski, and Pescetto. According to Hopkinson[1] the capacity of similar machines is proportional to the *cube* of their linear dimensions; the work wasted in magnetizing the field-magnets proportional to the linear dimensions, whilst that wasted in heat in the armature conductors is proportional to the square of the linear dimensions. Mascart and Joubert[2] place the capacity as low as the *square* of the linear dimensions, and draw the conclusion that small machines are preferable to large ones. Pescetto[3] arrives at similar conclusions. Rechniewski[4] follows Hopkinson in assigning n^3 as the proportion. Frölich[5] assigns the value n^4, and criticises the rule of the fifth power given by the author of this work and by Deprez, as involving an increase of n^3 in the current whilst there is an increase of only n^2 in the section of the conducting wires, which further involves that the density of the current in the wires must increase with the size of the machine, which is clearly impracticable. Storch[1] considers constant-current machines to be in a different category from constant-potential machines. Assuming equal intensity of magnetic field, equal peripheral velocity, and equal permissible current-density, he finds that in all machines the ampere-turns requisite for excitation vary as the linear dimensions. For constant-current machines the capacity is proportional to n^3, that is to say to the weight of the machine, or to the volume of copper on the armature. For constant-potential machines he finds the total length of wire on the armature to be independent of the dimensions of the machines; the number of external armature conductors to vary inversely as the linear dimensions; whilst the capacity of the machines is found to vary as n^4, though with undue heating, unless the volume of copper on the armature is also increased as n^4. Storch and Rechniewski agree with Hopkinson that the work lost in field-magnets decreases relatively to that lost in armatures, with an increase in the linear dimensions. On the other hand, increase in the size of the moving masses increases the liability to waste of power by eddy-currents.

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[1] *Proc. Inst. Civil Engineers*, April 1883.

[2] *Leçons sur l'Électricité*, ii. 815, 1886.

[3] *L'Electricien*, xi. 357, 1887.

[4] *La Lumière Électrique*, xxii. 311.

[5] *Die dynamoelektrische Maschine*, p. 168, 1886.

Recent contributions to the discussion come from Mr. Kapp[2] and Professor Ayrton.[3] Kapp proposes that the speeds of rotation shall be assumed to vary inversely as the linear dimensions, so as to put all machines into equal conditions as regards strains from centrifugal force, and that all the similar machines shall be considered as being worked up to the same safe limit of heating. This involves that the work wasted internally in heat shall be proportional to surface or as $1 : n^2$. The resistances, both magnetic and electric, of the field-magnets will be proportional to n^{-1}, and the exciting powers to $n^{\frac{3}{2}}$. The intensities of field will be proportional to $n^{\frac{1}{4}}$, and the electromotive-forces to $n^{\frac{5}{4}}$. The diameters of wires allowed are as n^1 on the magnets and $n^{1\frac{1}{2}}$ on the armatures; the resistances of armatures will be proportional to n^{-2}, and the permissible current to n^2. It follows at once that the capacities of the machine (in watts) will vary as $n^{3\frac{1}{2}}$, whilst the work wasted will vary as n^2: hence the economic coefficient will increase with the size of the machine. Kapp gives the cost of machines as proportional to $n^{2\frac{1}{2}}$, whence it follows that the cost of a dynamo per unit of output (say per lamp) varies inversely as its linear dimensions. He gives the following illustrative table:—

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[1] *Centralblatt für Elektrotechnik*, viii. 544, 594, and 743, 1886.

[2] *Proc. Inst. Civil Engineers*, lxxxiii. 36, 1886.

[3] *Ibid.*, p. 116.

Diameter of armature (inches)	10	15
Revolutions per minute	1000	670
Number of glow-lamps	150	620
Weight (in hundredweights)	10	34
Price	100*l.*	276*l.*
Price per lamp	13*s.* 4*d.*	8*s.* 11*d.*
Electrical efficiency (per cent.)	80	89

Professor Ayrton assumes that the speeds of similar machines may be safely put as inversely proportional to the square-roots of the linear dimensions or as to $n^{-\frac{1}{2}}$ instead of n^{-1}, for the number and the strength of the binding wires could easily be increased in the larger machines. In the larger machines the smaller relative space required for clearance makes admissible the increase of the current in proportion to n^2. But this increased current would magnetize the iron more highly in proportion, and the electromotive-force would be greater than $n^{1\frac{1}{2}}$, probably nearer $n^{1\cdot7}$, bringing up the capacity to be proportional to $n^{3\cdot7}$.

The common opinion of dynamo constructors appears to be that the capacity of dynamos is, for similar machines, a little greater than in proportion to the weight.

Esson[1] has discussed this question from the point of view of multipolar machines, and finds it a matter of appropriate design whether the efficiency increases or decreases when machines are enlarged in size.

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[1] *Journal Inst. Electrical Engineers*, xx. 265, 1891.

CHAPTER VI.

MAGNETIC PRINCIPLES; AND THE MAGNETIC PROPERTIES OF IRON.

As all dynamo-electric machines are based on magnetic principles, it is needful that these should be understood fully. Inasmuch as the field-magnets of dynamos are electromagnets, the iron cores of which are excited by electric currents circulating in surrounding coils, it becomes a matter of primary importance to us to know what is the law that governs the electromagnet. If we once know the relation that subsists between the exciting current and the magnetism that is produced by it, we can apply this knowledge to the design of dynamos: for such knowledge will enable us to calculate beforehand the size of field-magnet and the number and gauge of coils that will be required in a dynamo that is to furnish any given amount of electric energy. It will be necessary first to define the terms used; then we shall give some account of the facts and of the properties of iron of different kinds; incidentally there will follow an account of the various algebraic rules that have been suggested to represent approximately the law of the electromagnet. In Chapter VII. follow some all-important considerations respecting the magnetic circuit and its theory; some examples and useful rules will be given, and lastly, the various forms given to field-magnets will be discussed and calculations respecting them will be given.

DEFINITIONS AND GENERAL PROPERTIES.[1]

Unit of Magnetism.—The unit quantity of magnetism (as accepted internationally) at any magnetic pole, is defined as being such that it will repel a similar equal quantity situated at a distance of one centimetre, in air, with a force of 1 *dyne.*

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[1] Any one who is not familiar with the measurement of magnetic quantities ought very carefully to read Appendix A, on Electric and Magnetic Units. It

Intensity of Magnetic Field.—We have seen in Chapter III. that every magnet is surrounded by a certain "field," within which magnetic force is observable. We may completely specify the properties of the field at any point by measuring the *strength* and the *direction* of that force—that is, by measuring the "*intensity of the field*" and the direction of the lines of force. *The "intensity of the field" at any point is measured by the force with which it acts on a unit magnetic pole placed at that point.* Hence, *unit intensity of field is that intensity of field which acts on a unit pole with a force of one dyne.* There is therefore a field of unit intensity at a point one centimetre distant from the pole of a magnet of unit strength. Suppose a magnet pole, whose strength is m, placed in a field at a point where the intensity is H, then the force will be m times as great as if the pole were of unit strength, and the amount of the force (in dynes) can be calculated by simply multiplying together the strength of the magnetism of the pole and the intensity of the field; or,

$$f = m \times \mathrm{H}$$

Magnetic Lines.—It is possible, in every magnetic field, to draw through any given point, a line in such a direction that it represents the direction of the magnetic force at that point of the field (Fig. 10, p. 24). The iron filing curves formed round magnets show the forms of the otherwise invisible magnetic lines. Even when such lines are not actually drawn, they may be supposed to be drawn; we may even conceive the whole of the space in the magnetic field to be traversed by such lines. Faraday was the first to give a quantitative significa-

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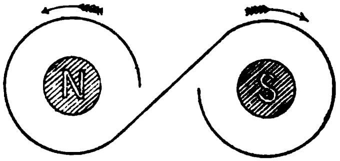
is also strongly recommended that the reader should make himself familiar with the elementary theory of magnetic phenomena. The Author's 'Elementary Lessons in Electricity and Magnetism,' published by Messrs. Macmillan and Co., will explain the terms and fundamental facts. The Author's recent work on 'The Electromagnet,' published by Messrs. Spon, contains a fuller account of the magnetic properties of iron, and of the design and construction of electromagnets.

tion to the conception of magnetic lines. We may use them to specify not only the *direction* but also the *magnitude* of the magnetic forces by adopting the following convention:—Let there be drawn as many lines per square centimetre as there are dynes (per unit pole) of force at the point in question. The symbol H may then be read to mean *either* the number of dynes on a unit pole or the number of lines per square centimetre.

We take as a measure of the intensity of the field at any point the number of lines of force that pass through a square centimetre of surface placed across the field at that point. *It follows that a unit magnet pole will have* 4π *lines of force proceeding from it:* for there is unit field at unit distance away, or one line of force per square centimetre; and there are 4π square centimetres of surface on a sphere of unit radius drawn round the pole. A magnet whose pole strength is m, has therefore $4\pi m$ lines of force running through the steel and diverging at its pole.

Polarity.—It is a familiar fact that the polarity of an electromagnet depends upon the sense in which the current is flowing around it. Various rules for remembering the relation of the electric flow and the magnetic force have been given. One of them that is useful is that when one is looking at the north pole of an electromagnet, the current will be flowing around that pole in the sense opposite to that in which the hands of a clock are seen to revolve. This necessitates the connexion of the bobbins of a two-pole electromagnet in such a way that the currents shall circulate as indicated in the manner depicted in Fig. 84. Another useful rule, suggested by Maxwell, is illustrated by Fig. 85, namely, that the sense of the circulation of the current (whether right or left-handed), and the positive direction of the resulting magnetic

FIG. 84.



CIRCULATION OF CURRENT AROUND A TWO-POLE ELECTROMAGNET.

force, are related together in the same way as the rotation and the travel of a right-handed screw are associated with forward travel. Right-handed circulation of a current is associated with a magnetic force tending to produce north polarity at the forward end of the core.

FIG. 85.

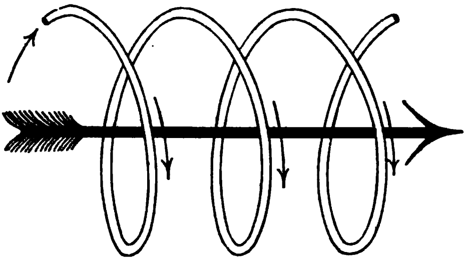


DIAGRAM ILLUSTRATING RELATION OF MAGNETIZING CURRENT AND RESULTING MAGNETIC FORCE.

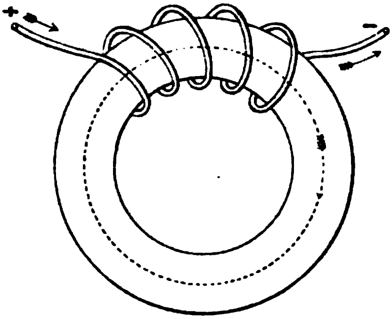
ELECTROMAGNETIC RULES.

Since the field-magnet is in almost all dynamos an electromagnet of iron magnetized by keeping an electric current circulating around it, it will be necessary to lay down a few elementary propositions dealing with the relation between electric currents and magnetic forces.

1. *Magnetomotive Force*, or Total Magnetizing Power of Electric Current circulating in a Coil.—It is found that when a current flows along in a copper wire that is coiled in several turns around a core, and is thus made to circulate around an interior magnetic circuit, the magnetizing power or tendency of this circulation of electricity is proportional both to the strength of the current so circulating and to the number of turns in the coil. If other things are equal, the total magnetizing power depends on nothing else but these two matters; being independent of the size or material of the wire, and of its shape, and is the same whether the spirals are close together or wide apart. If S stands for the number of *spirals* in the coil, and i be the number of *amperes* of current

that are flowing, then S multiplied by i will be the number of *ampere-turns* of circulation of current. It is experimentally proved that twenty amperes circulating around five turns exert precisely the same magnetizing power as one ampere circulating one hundred times, or as one hundred amperes circulating once around the core. In each of these cases the circulation of current is one hundred ampere-turns. To calculate from this the value, in absolute C.G.S. units, of the magnetomotive force, it is requisite to multiply the ampere-turns by $\frac{4}{10}\pi$, or by 1·257. Or, in symbols.

FIG. 86.



MAGNETIZING COIL WOUND AROUND A MAGNETIC CIRCUIT.

$$\text{Magnetomotive force} = 1{\cdot}257 \times S\,i.$$

It is possible to avoid the use of this multiplier by taking the ampere-turns themselves as the magnetomotive force. In that case one applies a coefficient to the calculation of the reluctance of the circuit (see p. 409).

Some writers call the magnetomotive force the "line-integral of the magnetic forces."

2. *Intensity of Magnetic Force at any point in a long Magnetizing Coil.*—The preceding expression for the total magnetizing power of a coil does not give any information about the variation of the magnetic force at different parts. If in Fig. 86 a closed curve be drawn (the dotted curve) passing through all the spirals, and the question be asked, "What is the intensity of the magnetic force at various points

on this curve?" it must be replied that the intensity of the force will vary greatly from point to point, being greatest at the middle of that part of the curve which lies within the spirals. If a uniformly-wound coil were constructed of very great length (say at least one hundred times its own diameter), the intensity of the magnetic force would be very nearly uniformly great all along its axis, until quite close to the ends of the coil, where it rapidly falls off. The expression for the value of H at any point along the axis (save near the ends) of such a long coil is found by considering the magnetomotive force as distributed uniformly along its length; or, in symbols, where l stands for the length of the coil, in centimetres.

$$H = \frac{4\pi}{10}\frac{S\,i}{l} = 1\cdot257 \text{ times the ampere-turns per centimetre of length.}$$

Or, if the length is given in inches:

$$H = 0\cdot495 \text{ times the ampere-turns per inch.}$$

Or, if it is desired to express the intensity of the magnetic force in lines *per square inch* (see p. 142) instead of per square centimetre, we shall have:—

$$H_{''} = 3\cdot192 \times \text{the ampere-turns per inch.}$$

In the case where a wire is wound in an annular coil upon an iron ring, so that there are no ends to the coil, H is uniform at all points along the closed curve drawn within the coil, and is calculated as above, taking the mean length along the body of the ring as l. It is obvious that when H is uniform, $H \times l$ gives the total magnetizing power or magnetomotive force.

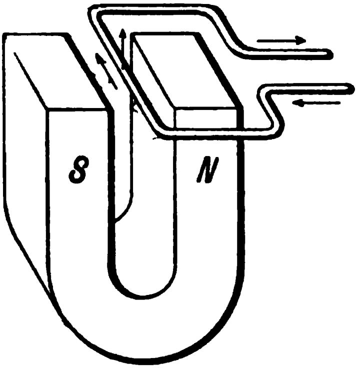
3. *Intensity of Magnetic Force at centre of a single Ring.*—At the centre of a single ring or circular loop of wire carrying current of i amperes, and of radius r centimetres, the intensity of the magnetic force is calculated by the formula

$$H = \frac{2\pi i}{10\,r} = 0\cdot6284 \times \frac{\text{amperes}}{\text{radius}}.$$

This is the case of a tangent galvanometer ring; the number needing to be multiplied by S, if there are S turns in the ring.

4. *Force on Conductor* (carrying current) *in a Magnetic Field.*—Suppose a magnetic field is furnished by a permanent magnet (Fig. 87), and that a conducting wire carrying an electric current is brought into the magnetic field, it is observed to experience a mechanical force in a direction at right angles to its own length, and at right angles to the magnetic lines of the field. In the figure the direction of the flux of magnetic lines is horizontal from right to left between the limbs of the magnet; the direction of the current is horizontal from front to back; and the resulting mechanical force will urge the conductor upwards, as shown by the arrow. Reversing the current would, of course, result in a downward force.

FIG. 87.



ACTION OF MAGNETIC FIELD ON CONDUCTOR CARRYING CURRENT.

The magnitude of this force can be calculated as follows:—Assume the field to be of uniform intensity H, and that the length (centimetres) of conductor lying squarely across the field is l. Then if i is the number of amperes of current, the force (in dynes) will be given by the rule

$$f = \mathrm{H}\, l\, i \div 10 = \mathrm{H}_{''}\, l''\, i \div 25{\cdot}43$$

or in grains' weight

$$f = \mathrm{H}_{''}\, l''\, i \div 161.$$

5. *Work done by Conductor* (carrying current) *in moving across Magnetic Field.*—If the conductor moves across a breadth b (centimetres) of the magnetic field, the work done will be expressed (in ergs) as follows:—

$$w = f\, b = b\, \mathrm{H}\, l\, i \div 10.$$

But $b\, l$ is the area of field swept out; and this area multiplied by the number of magnetic lines per square centimetre (H) gives the whole number N of magnetic lines cut in the operation: whence

$$w = \mathrm{N}\, i \div 10.$$

Proof:—This matter may be independently deduced as follows:—By definition of electric potential, the work done in moving Q units of electricity through difference of potential $\mathrm{V}_1 - \mathrm{V}_2$ is

$$w = \mathrm{Q}\,(\mathrm{V}_1 - \mathrm{V}_2).$$

But in cutting N lines of magnetic field in a time of t seconds there is generated an electromotive-force $= \mathrm{N} \div t$, and this constitutes the difference of electric potential $\mathrm{V}_1 - \mathrm{V}_2$ and may be substituted for it.

Further, if the current i is expressed in amperes, the quantity Q of electricity expressed in absolute C.G.S. units conveyed through the circuit in t seconds, will be $= i\, t \div 10$.

Substituting the latter value for Q and the former for $\mathrm{V}_1 - \mathrm{V}_2$, one at once obtains the result:—

$$w = \mathrm{N}\, i \div 10, \text{ as before.}$$

Intensity of Magnetization: Magnetic Susceptibility and Magnetic Permeability.—When a piece of magnetic metal is placed in a magnetic field, some of the lines of magnetic force run through it and magnetize it. The intensity of its magnetization will depend upon the intensity of the field into which it is put and upon the metal itself. There are two ways of looking at the matter, each of which has its advantages. We may think of the magnetism of the iron or other metal as something resident on the polar surfaces, and expressed therefore in units of magnetism: this is the old way, adopted at a time when magnetism was regarded as a fluid. Or, we may think about the internal condition of the piece of metal, and about the number of magnetic lines that are running through it and emerging from it into the surrounding space. This is the more modern way.

The fact that soft iron placed in the magnetic field becomes highly magnetic, may then be expressed in the following two ways:—(1) when iron is placed in a magnetic field the magnetic lines gather themselves up and run in greater quantities through the space now occupied by iron, for iron is very *permeable* to the magnetic lines,[1] or is a good conductor of them; (2) iron when placed in the magnetic field develops strong poles on its end surfaces, being highly *susceptible* to the reception of magnetism. Each of these ideas may be rendered exact by the introduction of coefficients of *permeability* and of *susceptibility* respectively.

The *permeability or coefficient of magnetic induction* is based on the notion of the whole mass of iron being permeated by the magnetic lines. The number of magnetic lines that run through unit area of cross-section, at any point is called "the magnetic induction" at that point; it is denoted[2] by the letter B. The ratio between the magnetic induction and the magnetizing force H producing it is expressed by a numerical coefficient of induction, or *permeability*, μ. We therefore write

$$\mathsf{B} = \mu \mathsf{H}$$

or

$$\mu = \frac{\mathsf{B}}{\mathsf{H}}$$

This coefficient is always positive: for empty space or air it is 1; for magnetic materials it is greater than 1; for diamagnetic materials it is slightly less than 1. The student may think of it in the following way: Suppose a certain magnetizing force to act in a certain direction, there would naturally result from its action induction along a certain number of magnetic lines (or so-called lines of force), and in air the number of lines would numerically represent the magnetizing force. But if the space considered were occupied by iron the same magnetizing force would induce many more lines; iron having a sort of multiplying power, or specific inductive capacity, or conductivity, for the magnetic lines. For example, a certain specimen of iron, when subjected to a magnetic force capable of creating, in air, 50 magnetic lines to the square centimetre, was found to be permeated by no fewer than 16,062 magnetic lines per square centimetre. Dividing the latter figure by the former, gives as the value of the permeability at this stage of the magnetization 321, or the permeability of the iron is 321 times that of air. The permeability of such non-magnetic materials as silk, cotton, and other insulators, also of brass, copper, and all the non-magnetic metals, is taken as 1, being practically the same as that of the air.

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[1] Some authorities make a distinction between magnetic lines of force (those which would exist in air) and magnetic lines of induction, or those which exist in any material over and above the number which would exist in air alone. The distinction is entirely useless, for all magnetic lines have the same properties. I call them all simply "magnetic lines."

[2] The following are the various ways of expressing the three definitions:—

B—The internal magnetization.
  The magnetic induction.
  The induction.
  The intensity of the induction.
  The permeation.
  The number of lines per square centimetre in the material.

H—The magnetizing force at a point.
  The magnetic force at a point.
  The intensity of the magnetic force.
  The number of lines per square centimetre that there would be in air.

μ—The magnetic permeability.
  The permeability.
  The specific conductivity for magnetic lines.
  The magnetic multiplying power of the material.

The *susceptibility* or *coefficient* of (surface) *magnetization* is now seldom used. Suppose a bar magnet to have m units of magnetism on each pole, and the length between the two poles to be l, the product $m \times l$ is called its *magnetic moment;* and the magnetic moment divided by its volume is called its *intensity* of magnetization: this term being intended, though based on the surface-unit of pole-strength, to convey an idea as to the internal magnetic state. Now, supposing this intensity of magnetization—for which the symbol is I—were due to the iron having been put into a magnetic field of intensity H, the ratio between these two is called the *susceptibility*, and for it the symbol k is used. So we may write

$$\mathsf{I} = k\,\mathsf{H},$$

or

$$k = \frac{\mathsf{I}}{\mathsf{H}}$$

This may be looked upon as saying that for every magnetic line in the magnetizing field there will be k units of magnetism on the end surface of the bar of iron.

These two coefficients are connected in the following way; since each line produces k units of magnetism, and from each unit 4π lines proceed outwards, there will be $4\pi k$ lines added by the iron to each line in the air: or

$$\mu = 1 + 4\pi k$$

and

$$B = H + 4\pi I.$$

This mode of expressing the facts is, however, complicated by the fact of the tendency in all kinds of iron to magnetic saturation. In all kinds of iron the magnetizability of the material becomes diminished as the actual magnetization is pushed further. In other words, when a piece of iron has been magnetized up to a certain degree, it becomes from that degree onward, less permeable to further magnetization, and though actual saturation is never reached, there is a practical limit beyond which the magnetization cannot well be pushed. Joule was one of the first to establish this tendency toward magnetic saturation. Modern researches have shown numerically how the permeability diminishes as the magnetization is pushed to higher stages. The practical limit of the magnetization, B, in good wrought iron, is about 20,000 magnetic lines to the square centimetre, or about 125,000 lines to the square inch; and, in cast iron the practical saturation limit is nearly 12,000 lines per square centimetre, or about 70,000 lines per square inch.

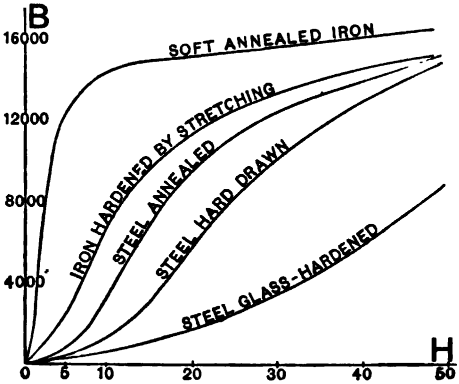
In designing electromagnets, before calculations can be made as to the size of a piece of iron required for the core of a magnet for any particular purpose, it is necessary to know the magnetic properties of that piece of iron; for it is obvious that if the iron be of inferior magnetic permeability, a larger piece of it will be required in order to produce the same magnetic effect as might be produced with a smaller piece of higher permeability. Or again, the piece having inferior permeability will require to have more copper wire wound on it;

for in order to bring up its magnetization to the required point, it must be subjected to higher magnetizing forces than would be necessary if a piece of higher permeability had been selected.

CURVES OF MAGNETIZATION.

A convenient mode of studying the magnetic facts respecting any particular brand of iron is to plot on a diagram the curve of magnetization—*i.e.* the curve in which the values, plotted horizontally, represent the magnetic force, H, and the values plotted vertically those that correspond to the respective magnetization, B. In Fig. 88, which is modified from the researches of Professor Ewing,[1] are given five curves, relating to soft iron, hardened iron, annealed steel, hard-drawn steel, and glass-hard steel. It will be noticed that all these curves have the same general form. For small values of H the values of B are small, and as H is increased B increases also. Further, the curve rises very suddenly, at least with all the softer sorts of iron, and then bends over and becomes nearly horizontal. When the magnetization is in the stage below the bend of the curve, the iron is said to be

FIG. 88.



CURVES OF MAGNETIZATION OF VARIOUS SORTS OF IRON.

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[1] *Phil. Trans.*, 1885.

far from the state of saturation. But when the magnetization has been pushed beyond the bend of the curve the iron is said to be in the stage approaching saturation; because at this stage of magnetization it requires a large increase in the magnetizing force to produce even a very small increase in the magnetization. It will be noted that for soft wrought iron the stage of approaching saturation sets in when B has attained the value of about 16,000 lines per square centimetre; or when H has been raised to the value of about 50. As we shall see, it is not economical to push B beyond this limit; or in other words it does not pay to use stronger magnetic forces than those of about H = 50.

METHODS OF MEASURING PERMEABILITY.

There are four sorts of experimental methods of measuring permeability:—

I. Magnetometric methods.
II. Balance methods.
III. Inductive methods.
IV. Traction methods.

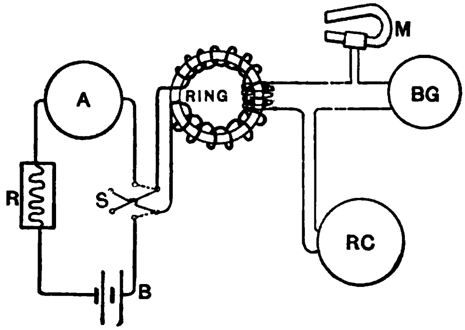
I. *Magnetometric Methods.*—These consist in surrounding a bar of the iron in question by a magnetizing coil, and observing the deflection its magnetization produces in a magnetometer.

II. *Balance Methods.*—These methods are a variety of the preceding; a compensating magnet being employed to balance the effect produced by the magnetized iron on the magnetometer needle. The method has received a more definite application in the magnetic balance of Professor Hughes. Neither of these methods are, however, to be compared with those that follow.

III. *Inductive Methods.*—There are several varieties of these, but all depend on the generation of a transient induction current in an exploring coil which surrounds the specimen of iron; the integral current being proportional to the number of magnetic lines introduced into, or withdrawn from the circuit of the exploring coil. Three varieties may be mentioned.

(*A.*) *Ring Method.*—In this method, due to Kirchhoff, the iron under examination is made up into a ring, which is wound with a primary, or exciting coil, and with a secondary, or exploring coil. Determinations on this plan have been made by Stoletow, Rowland, Bosanquet, and Ewing; also by Hopkinson. Rowland's arrangement of the experiment is shown in Fig. 89, in which B is the exciting battery; S the switch for turning on or reversing the current in the exciting coil wound on the iron ring; R a variable resistance; A an amperemeter; and B G the ballistic galvanometer, the first swing of which measures the integral induced current. R C is an earth-inductor or reversing coil wherewith to calibrate the readings of the galvanometer; and above is an arrangement of a coil and a magnet to assist in bringing the swinging needle to rest between the observations. The exciting coil and the exploring coil are both wound upon the ring; the former is distinguished by being drawn with a thicker line. The usual mode of procedure is to begin with a feeble exciting current, which is suddenly reversed, and then reversed back. The current is then increased, reversed, and re-reversed; and so on, until the strongest available points are reached. The values of the magnetizing force H are calculated from the observed value of the current by the

Fig. 89.



Ring Method of Measuring Permeability (Rowland's arrangement).

following rule:—If the strength of the current, as measured by the amperemeter, be i, the number of spires of the exciting coil S, and the length in centimetres of the coil (*i.e.* the mean circumference of the ring) be l, then H is given (see p. 126) by the formula—

$$H = \frac{4\pi}{10} \times \frac{S\,i}{l} = 1{\cdot}257 \times \frac{S\,i}{l}.$$

Bosanquet, applying this method to a number of iron rings, obtained some important results, and settled the debated question whether the outer layers of an iron core shield the inner layers from the influence of magnetizing forces. Were this the case, thin rings should show higher values of B than do the thicker rings; but Bosanquet found nothing of the kind.

(*B.*) *Bar Method.*—This method consists in employing a long bar of iron instead of a ring. It is covered from end to end with the exciting coil, but the exploring coil consists of but a few turns of wire situated just over the middle part of the bar. Rowland, Bosanquet, and Ewing have all employed this variety of method; and Ewing specially used bars, the length of which was more than a hundred times their diameter, in order to get rid of errors arising from end-effects.

(*C.*) *Divided Bar Method.*—This method, due to Dr. Hopkinson,[1] illustrated by Fig. 90, employs a block of annealed wrought iron about 18 inches long, 6½ inches wide, 2 inches deep, out of the middle of which is cut a rectangular space to receive the magnetizing coils. The test samples of iron consist of two rods, each 12·65 mm. in diameter, turned carefully true, and slide in through holes bored in the ends of the iron block. These two rods meet in the middle, their ends being faced true so as to make a good contact. One of them is secured firmly, and the other has a handle fixed to it, by means of which it can be withdrawn. The two large magnetizing coils do not meet, a space being left between them. Into this space is introduced the little exploring coil, wound upon an ivory bobbin, through the eye of which passes the end of the movable rod. The exploring coil is connected to the ballistic galvanometer, B G, and is attached to an india-rubber spring (not shown in the figure), which, when the rod

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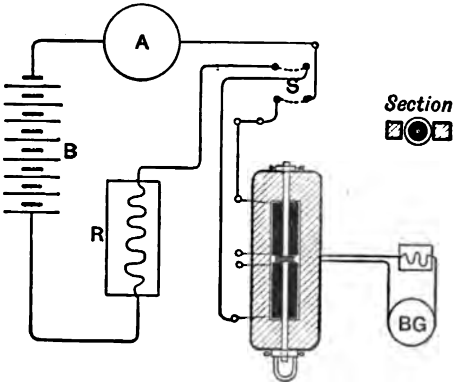
[1] *Phil. Trans.*, p. 456, 1885.

FIG. 90.



HOPKINSON'S DIVIDED BAR METHOD OF MEASURING MAGNETIC PERMEABILITY.

is suddenly pulled back, causes it to leap entirely out of the magnetic field. The exploring coil had 350 turns of fine wire; the two magnetizing coils had 2008 effective turns. The magnetizing current, generated by a battery, B, of eight Grove cells, was regulated by a variable liquid resistance, R, and by a shunt resistance. A reversing switch and an amperemeter, A, were included in the magnetizing circuit. By means of this apparatus the sample rods to be experimented upon could be submitted to any magnetizing forces, small or large, and the actual magnetic condition could be examined at any time by breaking the circuit and simultaneously withdrawing the movable rod. This apparatus, therefore, permitted the observation separately of a series of increasing (or decreasing) magnetizations without any intermediate reversals of the entire current.

The results obtained by Hopkinson are described on pp. 139 to 145.

To facilitate the operation of making observations on new brands of iron, Mr. J. Swinburne has recently[1] devised a method of experimenting which obviates the use of a ballistic galvanometer. The reader is referred to the original paper for further details.

TRACTION METHODS.

Another group of methods of measuring permeability is based upon the law of magnetic traction. Of these there are several varieties.

(*D.*) *Divided Ring Method.*—Mr. Shelford Bidwell has kindly lent me the apparatus with which he carried out this method. It consists of a ring of very soft charcoal iron rod 6·4 mm. in thickness, the external diameter being 8 cm., sawn into two half rings, and then each half carefully wound over with an exciting coil of insulated copper wire of 1929 convolutions in total. The two halves fit neatly together; and in this position it constitutes practically a continuous ring. When an exciting current is passed round the coils, both halves become magnetized and attract one another; the force required to pull them asunder is then measured. According to the law of traction, which will occupy us in the second lecture, the tractive force (over a given area of contact) is proportional to the square of the number of magnetic lines that pass from one surface to the other through the contact joint. Hence the force of traction may be used to determine B; and on calculating H as before, we can determine the permeability. The Table IV., on p. 147, gives a summary of Mr. Bidwell's results.

(*E.*) *Divided Rod Method.*—In this method, also used by Mr. Bidwell, an iron rod hooked at both ends was divided across the middle, and placed within a vertical surrounding magnetizing coil. One hook was hung up to an overhead support: to the lower hook was hung a scale-pan. Currents of gradually increasing strength were sent around the magnetizing coil from a battery of cells, and note was taken of the greatest weight which could in each case be placed in the scale-pan without tearing asunder the ends of the rods.

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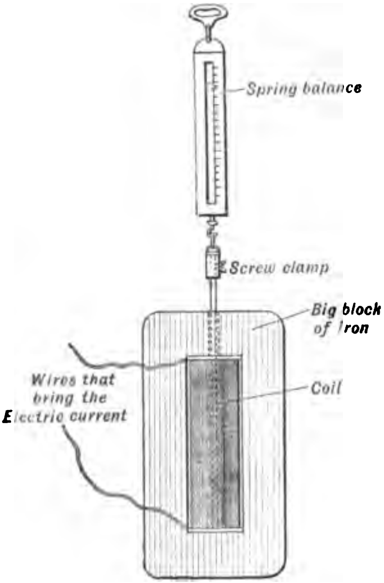
[1] See *The Electrician*, xxv. 648, October 10, 1890.

(*F.*) *Permeameter Method.*—This is a method devised for the purpose of testing specimens of iron. It is essentially a workshop method as distinguished from a laboratory method. It requires no ballistic galvanometer; and the iron does not need to be forged into a ring or wound with a coil. For carrying it out a simple instrument is needed, which the author denominates as a *permeameter.* Outwardly it has a general resemblance to Dr. Hopkinson's apparatus, and consists simply (Fig. 91) of a rectangular piece of soft wrought iron slotted out to receive a magnetizing coil, down the axis of which passes a brass tube. The block is 12 inches long, 6½ inches wide, and 3 inches in thickness. At one end the block is bored to receive the sample of iron that is to be tested. This consists simply of a thin rod about a foot long, one end of which must be carefully surfaced up. When it is placed inside the magnetizing coil, and the exciting current is turned on, the rod sticks tightly at its lower end to the surface of the iron block; and the force required to detach it (or rather the square root of that force) is a measure of the permeation of the magnetic lines through its end face. In the first permeameter which was constructed, the magnetizing coil is 13·64 cm. in length, and has 371 turns of wire. One ampere of exciting current consequently produces a magnetizing force of $H = 34$. The wire is thick enough to carry

FIG. 91.



THE PERMEAMETER.

30 amperes, so that it is easy to reach a magnetizing force of 1000. In a simple experiment the current used was 25 amperes. Two rods were taken of "charcoal iron" and "best iron" respectively, both of quarter-inch square stuff. A spring balance was used, graduated carefully and provided with an automatic catch, so that its index stops at the highest reading. The tractive force of the "charcoal" iron was about 12½ lb., while that of the "best" iron was only 7½ lb., so that B was about 19,000 in the charcoal iron, and H being 850, μ was about 22·3.

The formula for calculating B when the core is thus detached by a pull of P pounds, the area of contact being A square inches, is as follows:—

$$B = 1317 \times \sqrt{P \div A} + H.$$

The reason for adding H in the formula is that in this instrument the coil remains fixed, the core only being moved. Hence the pull is that due to $B - H$ lines.

(*G.*) *Traction Balance Method.*—Dr. H. G. Du Bois has recently described[1] a method in which the specimen of iron is placed within a coil between two cheeks of iron, thus constituting part of a magnetic circuit, of which another part is constituted by an iron beam, the attraction of which is measured, and thus the flux calculated.

RESULTS OF EXPERIMENTS ON DIFFERENT BRANDS OF IRON.

Thirty-five samples of various irons of known chemical composition were examined by Hopkinson, the two most important for present purposes being an annealed wrought iron and a grey cast iron, such as are used by Messrs. Mather and Platt in the construction of dynamo machines. Hopkinson embodied his results in curves, from which it is possible to construct, for purposes of reference, numerical tables of sufficient accuracy to serve for future calculations.

In Fig. 92 are given curves of magnetization for *annealed*

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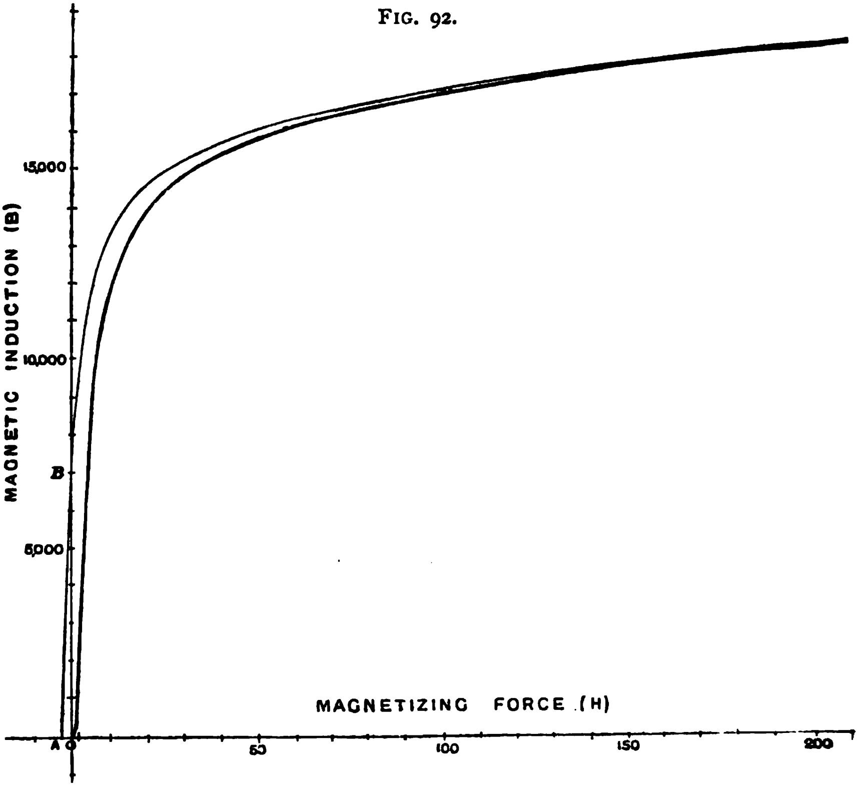
[1] *The Electrician*, xxvii. 635, Oct. 9, 1891.

wrought iron, obtained by the second method of experimenting by Dr. J. Hopkinson.[1] The black line shows the relation between the intensity of the magnetizing force H and the induction B during the process of increasing the magnetizing force from zero to about 220; and the light line shows the same relation during the process of decreasing the magnetizing force to zero, and then reversing it so as to remove the residual magnetic induction. Fig. 93 gives similar curves for a sample of *grey cast iron* such as is used by Messrs. Mather and Platt in building parts of dynamo machines.

FIG. 92.



Every sample of iron will show, on being tested, a similar set of facts which can be plotted down as a curve that is characteristic of the relation in question; but the curves for cast iron and steel always lie lower than those for wrought iron. Moreover, it will usually be noticed that when a fresh piece of iron or steel is subjected to a gradually increasing magnetizing force, the lowest part of the curve presents near its origin a small concavity (see Fig. 93), showing that there is a certain stage where under small magnetizing forces the permeability is greater than at the initial stage. This concavity is more pronounced in the case of hard iron and of steel than in the case of soft iron. But the curves differ in detail even in different specimens of the same sort of iron. In designing dynamos it is convenient to keep for reference a series of curves such as Fig. 92 and 93, made by careful observation on samples of the same iron as it is intended to use in construction.

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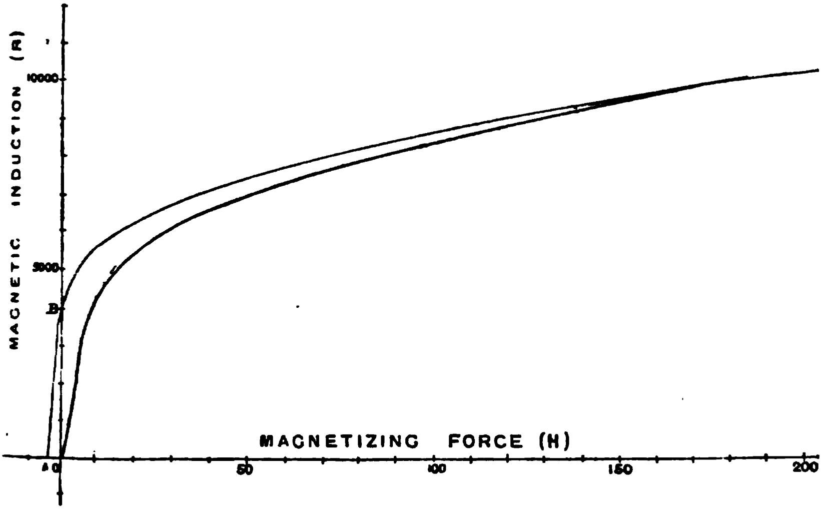
[1] Hopkinson, in *Phil. Trans.*, pt. ii. p. 455, 1885.

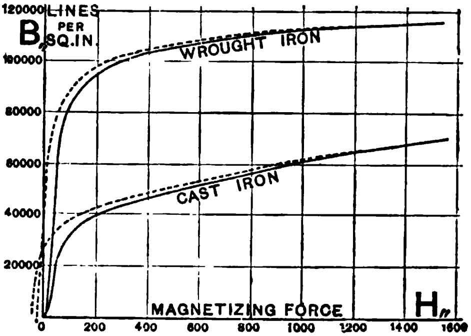
FIG. 93.



As we shall require to refer again to these curves when dealing with calculations of the magnetic circuit, it will be well to make the data as complete as possible. Many British engineers are, unfortunately, not familiar with the international metric system, and prefer to have the magnetic facts also stated in terms of square inch units instead of square cm. units. This change has been made in Fig. 94, and the symbols $B_{\prime\prime}$ and $H_{\prime\prime}$ are chosen to indicate the numbers of magnetic lines to the square inch in iron and in air respectively. The permeability, or multiplying power of the iron is the same, of course, in either measure. In Table III. are given the corresponding data in square inch measure; and in Table IV. the data in square centimetre measure for the same specimens of iron.

It will be noted that Hopkinson's curves are double, there being one curve for the ascending magnetizations, and a separate one, a little above the former, for descending magnetizations. This is a point of a little importance in designing electromagnets. Iron, and particularly hard sorts of iron, and steel, after having been subjected to a high degree of magnetizing force, and subsequently to a lesser magnetizing force, are found to retain a higher degree of magnetization than if the lower magnetizing force had been simply applied. For example, reference to Fig. 94 shows that the wrought iron, where subjected to a magnetizing force gradually rising from zero to $H_{\prime\prime} = 200$, exhibits a magnetization of $B_{\prime\prime} = 95{,}000$; but after $H_{\prime\prime}$ has been carried up to over 1000, and then reduced again to 200, $B_{\prime\prime}$ does not come down again to 95,000, but only to 98,000. Any sample of iron which

FIG. 94.



CURVES OF MAGNETIZATION OF IRON. (LINES PER SQ. IN.)

showed great retentive qualities, or in which the descending curve differs widely from the ascending curve, would be liable, if used in constructing a dynamo, to cause the dynamo, after having been highly magnetized, to work at a higher voltage than before. Cast iron shows more of this effect than wrought iron, and hard steel much more than either. For dynamo armatures only the softest iron must be used. For field-magnets most makers prefer wrought iron, but some use well-annealed cast iron. In very few cases is it worth while to make separate calculations for the ascending and descending curves of magnetization, since the magnetization is continually varying up and down. Accordingly, for the numerical data to be employed in calculations we shall employ the mean between the ascending and descending curves. These mean values are given in Tables I. and II.

TABLE I. (SQUARE CENTIMETRE UNITS.)

Annealed Wrought Iron.			Grey Cast Iron.		
B	μ	H	B	μ	H
5000	3000	1·66	4000	800	5
9000	2250	4	5000	500	10
10,000	2000	5	6000	279	21·5
11,000	1692	6·5	7000	133	42
12,000	1412	8·5	8000	100	80
13,000	1083	12	9000	71	127
14,000	823	17	10,000	53	188
15,000	526	28·5	11,000	37	292
16,000	320	50			
17,000	161	105			
18,000	90	200			
19,000	54	350			
20,000	30	666			

The mean values are plotted out from Tables I. and II. on a somewhat larger scale in Figs. 95 and 96, wherein the values of B are the abscissæ, and those of H are plotted vertically, the scale being on the right-hand side. On the same Figures are given also the plotting of the curves for B and μ, which are convenient for the purpose of calculation.

FIG. 95.

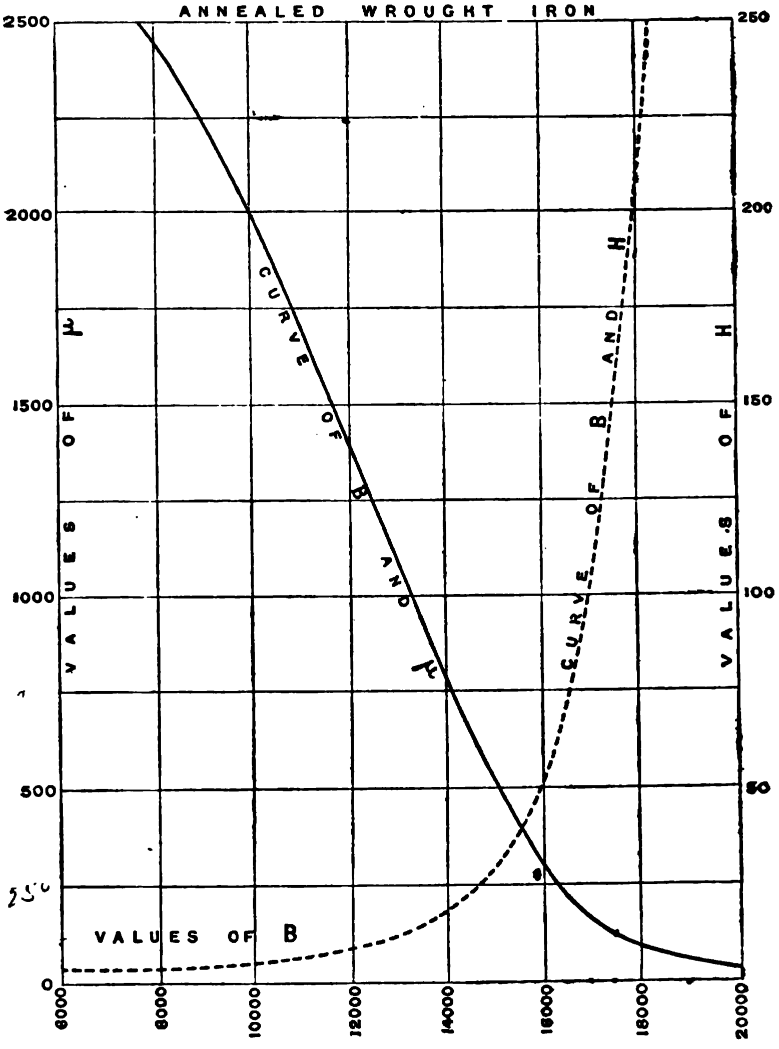


FIG. 96.

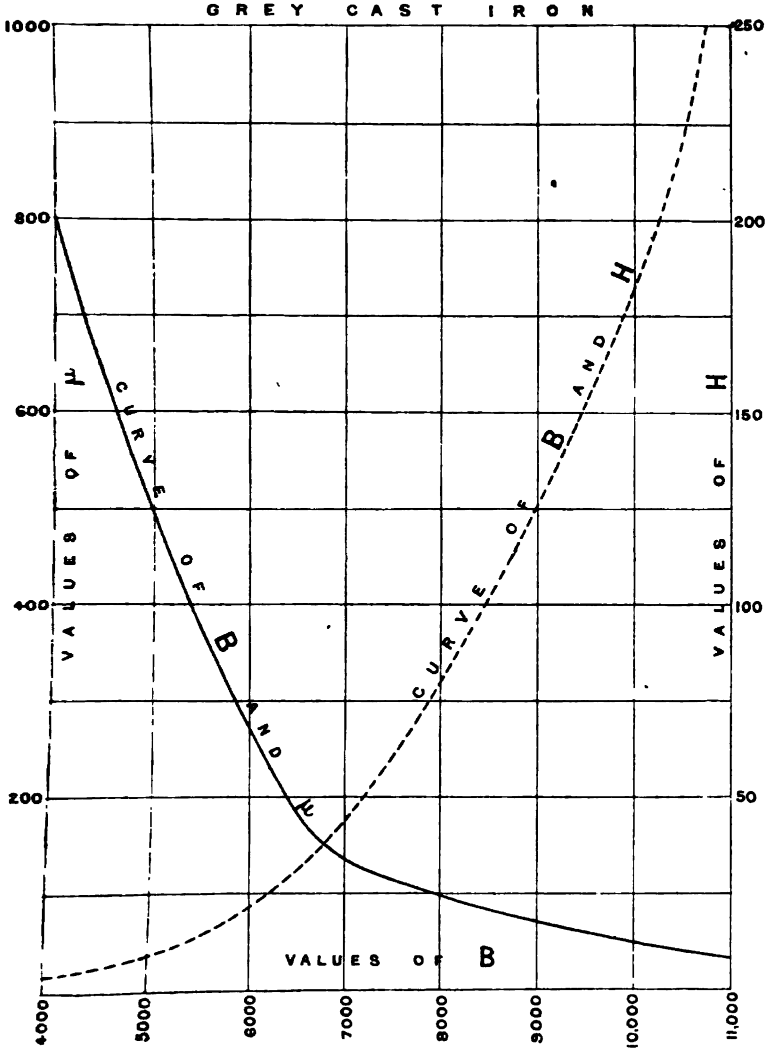

GREY CAST IRON
1000
800
600
400
200
250
200
150
100
50
VALUES OF μ
VALUES OF H
CURVE OF B AND μ
CURVE OF B AND H
VALUES OF B
4000
5000
6000
7000
8000
9000
10,000
11,000

TABLE II. (SQUARE INCH UNITS.)

Annealed Wrought Iron.			Grey Cast Iron.		
$B_{''}$	μ	$H_{''}$	$B_{''}$	μ	$H_{''}$
30,000	2926	10·2	25,000	833	30
40,000	2857	14	30,000	445	53·5
50,000	2392	20·9	40,000	245	163
60,000	2166	27·7	50,000	112	447
70,000	1750	40	60,000	64	940
80,000	1368	63	70,000	40	1750
90,000	856	105			
100,000	407	245			
110,000	161	686			
120,000	64	1850			
130,000	28	4500			
140,000	18	7630			

Bosanquet's data for five specimens of "Crown iron" are as follow:—

TABLE III.—VALUES OF B IN FIVE CROWN IRON RINGS.

Name.	G.	E.	F.	H.	K.
Mean Diam. Bar thickness.	21·5 cm. 2·535.	10·035 cm. 1·298.	22·1 cm. 1·292	10·735 cm. 0·7137	22·725 cm. 0·7544
H Magnetizing Force.'					
0·2	126	73	62	82	85
0·5	377	270	224	208	214
1	1,449	1,293	840	675	885
2	4,564	3,952	3,533	2,777	2,417
5	9,900	9,147	8,293	8,479	8,884
10	13,023	13,357	12,540	11,376	11,388
20	14,911	14,653	14,710	14,066	13,273
50	16,217	15,704	16,062	15,174	13,890
100	17,148	16,677	17,900	16,134	14,837

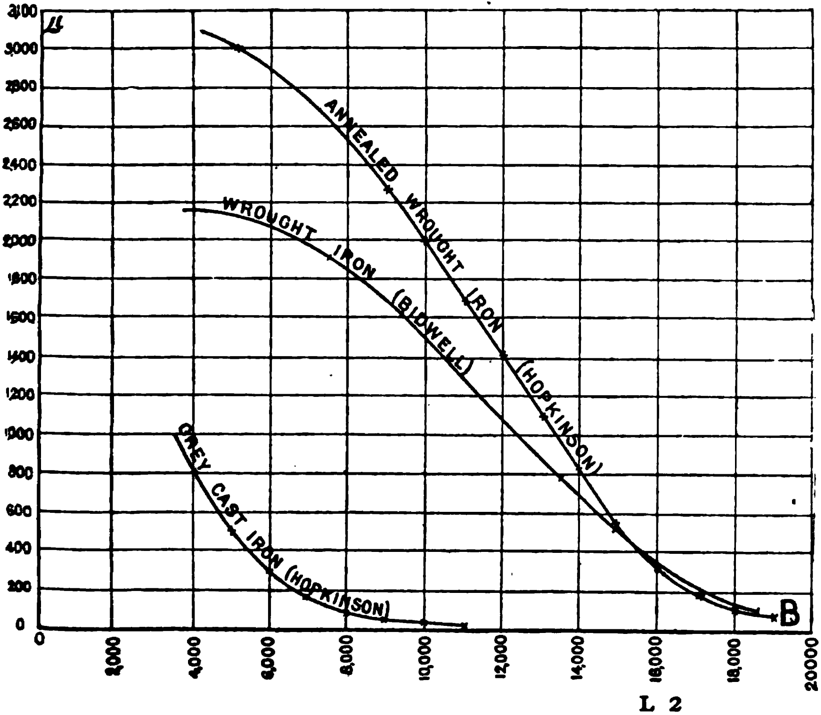
Bosanquet found a ring of Lowmoor iron to surpass all the samples of Crown iron, at $H = 50$ he found B over 17,000; and at $H = 100$, $B = 18{,}300$.

Bidwell, who pushed the magnetization further, using the traction method found the following results :—

TABLE IV.—SQUARE CENTIMETRE MEASURE.

Soft Charcoal Iron.		
B	μ	H
7,390	1899·1	3·9
11,550	1121·4	10·3
15,460	386·4	40
17,330	150·7	115
18,470	88·8	208
19,330	45·3	427
19,820	33·9	585

FIG. 97.



A very useful alternative mode of studying the results obtained by experiment is to construct curves, such as those of Fig. 97, in which the values of the permeability are plotted out vertically in correspondence with the values of B plotted horizontally, as in Figs. 95 and 96. It will be noticed that in the case of Hopkinson's specimen of annealed wrought iron between the points where $B = 7000$ and $B = 16{,}000$, the mean values of μ lie almost on a straight line, and might be approximately calculated from the equation

$$\mu = (17{,}000 - B) \div 3 \cdot 5.$$

LIMITS OF MAGNETIZATION AND PERMEABILITY.

In reviewing the results obtained, it will be noted that the curves of magnetization all possess the same general features, all tending toward a practical maximum, which, however, is different for different materials. Joule expressed the opinion that *no force of current could give an attraction equal to 200 lb. per square inch*, the greatest he actually attained being only 175 lb. per square inch. Rowland was of opinion that the limit was about 177 lb. per square inch for an ordinary good quality of iron, even with infinitely great exciting power. This would correspond roughly to a limiting value of B of about 17,500 lines to the sq. cm. This value has, however, been often surpassed. Bidwell obtained 19,820, or possibly a trifle more, as in Bidwell's calculation the value of H has been needlessly discounted. Hopkinson gives 18,250 for wrought iron, and 19,840 for mild Whitworth steel. Kapp gives 16,740 for wrought iron, 20,460 for charcoal iron in sheet, and 23,250 for charcoal iron in wire. Bosanquet found the highest value in the middle bit of a long bar to run up in one specimen to 21,428, in another to 29,388, in a third to 27,688. Ewing, working with extraordinary magnetic power by the "isthmus" method,[1] forced up the value of B in Lowmoor iron to 31,560 (when μ came down to 3), and subsequently to 45,350. This last figure corresponds to a traction exceeding 1000 lb. to the square inch.

[1] See *Electrician*, xxv. 307, 1890.

In the following table are given some of Ewing's figures relating to the magnetization of Swedish iron in very strong magnetic fields :—

TABLE V. (Square Centimetre Measure).—SWEDISH IRON.

H	B	μ
1,490	22,650	15·20
3,600	24,650	6·85
6,070	27,130	4·47
8,600	30,270	3·52
18,310	38,960	2·13
19,450	40,820	2·10
19,880	41,140	2·07

Cast iron falls far below these figures. Hopkinson, using a magnetizing force of 240, found the values of B to be 10,783 in grey cast iron, 12,408 in malleable cast iron, and 10,546 in mottled cast iron. Ewing, with a magnetizing force nearly fifty times as great, forced up the value of B in cast iron to 31,760. Mitis metal, which is a sort of cast wrought iron, being a wrought iron rendered fluid by addition of a small percentage of aluminium, is, as I have found, more magnetizable than cast iron, and not far inferior to wrought iron. It should form an excellent material for the cores of electromagnets.

It was at one time supposed that the values of B would show a limiting value at about 20,000, for example, in wrought iron. Ewing's figures obtained with enormous magnetizing forces, show that this is not so ; but, on the other hand, they show that B — H does tend to a limit. In other words, that part of B which is directly due to the presence of the iron, does tend to a true saturation limit. This maximum appears to be about 21,360 in wrought iron, and 15,580 in cast iron.

For further magnetic data the reader is referred to the writings of Hopkinson, Bosanquet, and Ewing, particularly to

Ewing's chapters on Magnetism in *The Electrician* of 1890–91. A digest of the researches of these authorities is to be found in the author's treatise on 'The Electromagnet.'

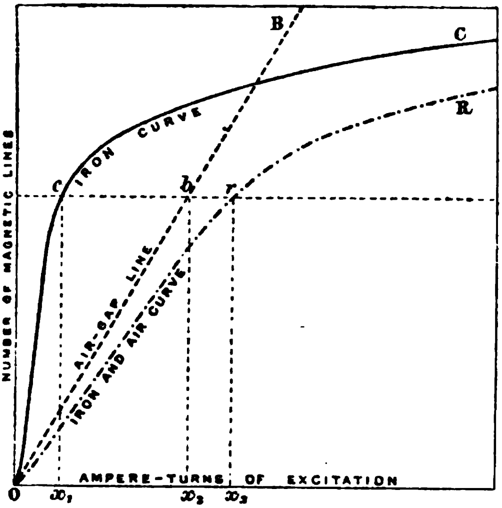
EFFECTS OF AIR-GAP IN MAGNETIC CIRCUIT.

All the preceding results refer exclusively to that which goes on in iron itself, the curves of magnetization referring to the magnetic materials only. They tell us (in terms of H) the magnetic force required to drive B lines of magnetization through a single cubic cm. of the material. If we are to deal with an actual piece of iron that is more than 1 sq. cm. in cross-section, and more than 1 cm. in length, all that is necessary to represent the facts (so long as we are dealing with magnetization that is entirely internal to the iron) is to change the scale of the curves. For example, suppose we are dealing with an iron ring made of a piece of square bar annealed wrought iron (of the same brand as Hopkinson used), the size of the iron being 2 cm. in the side, and its (mean) length 80 cm.; we shall now have to plot out (instead of B and H) N, the whole flux of magnetic lines within the section of the iron, and H l, the line-integral of the magnetizing force around the length of the iron circuit.

Taking the curve of B and H in Fig. 95, the scales will then have to be changed as follows:—Since the area is 4 sq. cm., N at any stage of the magnetization will be equal to four times B at that stage. Hence the point on the horizontal scale called B = 16,000, will now have to be called N = 64,000. And since l, the length of the bar, is 80 cm., the same point that now stands for H = 50 on the vertical scale (on the right side), which is the corresponding value of the magnetic force, will have to be called H l = 4000. With these changes of scales the curve will then serve to represent the magnetic behaviour of the whole ring; it will tell us how much integral magnetizing force we must exert (by means of a current in a coil) in order to drive up N, the total flux of magnetic lines, to any desired amount. If we know H l, it is easy to calculate the requisite ampere-turns, because (as shown on p. 125) the ampere-turns multiplied by 1·257 are equal to the line-integral of the magnetizing force.

But if there is an air-gap in the magnetic circuit, or if there is a gap filled with any non-magnetic material, seeing that all these things possess a permeability that is equal to that of air (*i. e.* = 1), it is evident that to force the same number of magnetic lines across a layer of such inferior permeability will necessitate an increase in the amount of magnetizing power that must be applied.

Fig. 98.



Curve of Magnetization of Magnetic Circuit with Air-gap.

This is made plainer by reference to Fig. 98, in which the curve O *c* C represents the relation between the number of magnetic lines in an iron bar and the number of ampere-turns of excitation (H $l \div 1{\cdot}257$) needed to force these magnetic lines through the iron. For example, to reach the height *c*, the excitation has to be of the value represented by the length O x_1. On the same diagram the line O *b* B represents the relation between the flux of magnetic lines across the air-gap and the ampere-turns required to force these lines across. If the gap were 1 sq. cm. in section, and 1 cm. long, 0·795 ampere-turns of current would produce field H = B = 1. In this case the gap is supposed to be of larger area and shorter than 1 cm., the line sloping up at such a slope that the length O x_2 represents the ampere-turns requisite to bring up the magnetic flux to *b*, which is at the same height on the scale as *a*. It is then easy to put the two things together, for the total amount of excitation required to force these magnetic lines through air and iron will (neglecting leakage) be the sum of the separate amounts. The point x_3 is chosen so that O x_3 is equal to the sum of O x_1, and O x_2, or that the distance of point *r* from the vertical axis is equal to the sum of the respective distances of *c* and *b*. If the same thing is done for a large number of corresponding points, the resultant curve O *r* R may be constructed from the two separate curves. It will be seen then that, in general, the presence of a gap in the magnetic circuit has the effect of causing the magnetic curve to rake over, *the initial slope being determined by the air-gap.*

The student should compare some interesting experiments made in Paris by M. Leduc,[1] who, however, falls into an error respecting tubular cores.

EFFECT OF JOINTS.

Being now in a position to calculate the additional magnetizing power required for forcing magnetic lines across an air-gap, we are prepared to discuss a matter that has been so far neglected, namely, the effect on the reluctance of the magnetic circuit of joints in the iron. Horse-shoe electromagnets are not always made of one piece of iron bent round. They are often made of two straight cores shouldered and screwed, or riveted into a yoke.

It is a matter purely for experiment to determine how far a transverse plane of section across the iron obstructs the flow of magnetic lines. Armatures, when in contact with the cores, are never in perfect contact, otherwise they would cohere without the application of any magnetizing force; they are only in imperfect contact, and the joint offers a considerable magnetic reluctance. This matter has been examined by Professor J. J. Thomson and Mr. Newall, in the Cambridge Philosophical Society's *Proceedings*, in 1887; and recently more fully by Professor Ewing, whose researches are published in the *Philosophical Magazine* for September, 1888. Ewing not only tried the effect of cutting and of facing up with true plane surfaces, but used different magnetizing forces, and also applied various external pressures to the joint. For our present purpose we need not enter into the questions of external pressures, but will summarise in Table VI. the results which Ewing found when his bar of wrought iron was cut across by section planes, first into two pieces, then into four, then into eight. The apparent permeability of the bar was reduced at every cut.

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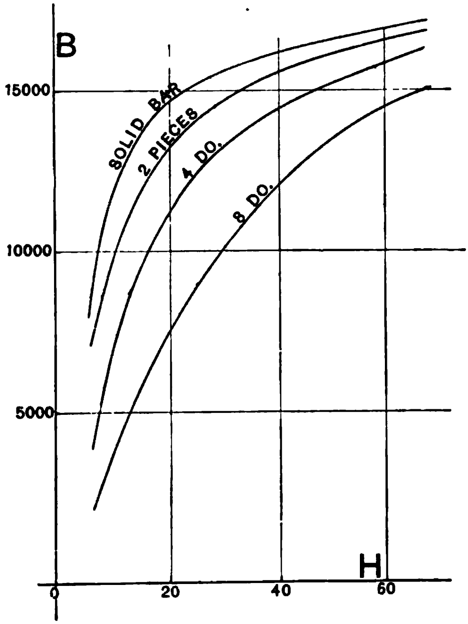
[1] *La Lumière Électrique*, xxviii. 520, 1888.

TABLE VI.—EFFECT OF JOINTS IN WROUGHT-IRON BAR (not compressed).

H	B				Mean thickness of equivalent air-space for one cut.		Thickness of iron of equivalent reluctance per cut.	
	Solid.	Cut in Two.	In Four.	In Eight.	Centimetres.	Inches.	Centimetres.	Inches.
7·5	8,500	6,900	4,809	2,600	0·0036	0·0014	4	1·57
15	13,400	11,550	8,900	5,550	0·0030	0·0012	2·53	1
30	15,350	14,550	12,940	9,800	0·0020	0·0008	1·10	0·433
50	16,400	15,950	15,000	13,300	0·0013	0·0005	0·43	0·169
70	17,100	16,840	16,120	15,200	0·0009	0·0004	0·22	0·087

Suppose we are working with the magnetization of our iron pushed to about 16,000 lines to the sq. cm. (*i. e.* about 150 lb. per square inch) traction, requiring a magnetising force of about H = 50; then, referring to Table VI., we see that each joint across the iron offers as much reluctance as would an air-gap 0·0005 of an inch in thickness, or adds as much reluctance as if an additional layer of iron about $\frac{1}{6}$th of an inch thick had been added. With small magnetizing forces the effect of having a cut across the iron with a good surface on it is about the same as though you had introduced a layer of air $\frac{1}{600}$th of an inch thick, or as though you had added to the iron circuit about 1 inch of extra length. With large magnetizing forces, however, this disappears, probably because of the attraction of the two surfaces across that cut. The stress in the magnetic circuit, with high magnetic forces running up to 15,000 or 20,000 lines to the sq. cm., will of itself put on a pressure of 130 to 230 lb. to the square inch,

FIG. 99.



EWING'S CURVES FOR EFFECT OF JOINTS.

and so these resistances are considerably reduced; they come down in fact to about $\frac{1}{20}$th of their initial value. When Ewing especially applied compressing forces, which were as large as 3200 lb. to the sq. in., which would of themselves ordinarily, in a continuous piece of iron, have diminished the magnetizability, he found the diminution of the magnetizability of iron itself was nearly compensated for by the better conduction of the cut surface. The old surface, cut and compressed in that way, closes up as it were magnetically—does not act like a cut at all; but at the same time you lose just as much as you gain, because the iron itself becomes less magnetizable.

The above results of Ewing's are further represented by the curves of magnetization drawn in Fig. 99. When the faces of a cut were carefully surfaced up to true planes, the disadvantageous effect of the cut was reduced considerably, and under the application of a heavy external pressure almost vanished.

The influence of compression was notable. When a compression of 3210 lb. per sq. in. (= 226 kilogrammes per sq. cm.) was applied to the iron bar, the joint showed, under magnetic forces, a reluctance which decreased as the magnetic force was increased. The following table gives the values of H and of B in the solid bar, and the bar after being cut, together with the mean thickness of the equivalent air-space.

TABLE VII.—EFFECT OF COMPRESSION ON JOINTS.

H	B { under compression of 3210 lb. per sq. inch.		Thickness of mean equivalent air-space. (Millimetres.)
	Solid bar.	Bar cut in eight.	
7·5	7,500	3,600	0·020
10	10,000	4,900	0·019
20	13,900	8,300	0·018
30	15,200	10,700	0·017
50	16,500	13,750	0·011
70	17,200	15,700	0·007

When various loads were tried, the effect of increasing the load, in a weak magnetic field, was practically to close up well-faced joints, as the following table shows.

TABLE VIII.—EFFECT OF VARIOUS LOADS ON JOINTS.

Load, kilos per sq. centimetre.	B (when H = 5).		Thickness of equivalent air-space. (Millimetres.)
	Before cutting.	After cutting and facing.	
0	5,600	4,700	0·022
56·5	5,400	4,670	0·020
131	4,700	4,200	0·017
169·5	4,050	3,800	0·010
226	3,650	3,650	0

EFFECTS OF STRESS.

A piece of iron when placed under stress is somewhat changed in its magnetic properties. If a longitudinal pull is applied to iron whilst it is being magnetized, it is found at first to increase its permeability, whilst a longitudinal push, tending to compress it, decreases its permeability. This is very well shown by the figures given in the second column of the last table, wherein it appears that a compression of 226 kilos. per sq. cm., or nearly 1½ ton per sq. in., brought down the value of B in a wrought-iron bar from 5600 to 3650; or diminished the permeability from 1120 to 730. Stress also impairs the softness of iron. A piece of annealed iron wire hardened by previous stretching, behaves more like a piece of steel, as may be seen by reference to Ewing's curves, Fig. 88, p. 132. Twisting stresses also affect the magnetic quality. The reader should consult Ewing's papers on magnetism.

Another important matter is that all such actions as hammering, rolling, twisting, and the like, impair the magnetic quality of annealed soft iron. Pieces of annealed wrought iron which have never been touched by a tool, provided they do not constitute actually closed magnetic circuits, show hardly any trace of residual magnetization, even after the application of magnetic forces. But the touch of the file will at once spoil it. The continual hammering of the armature of an electromagnet against the poles may in time produce a similar hardening effect.

EFFECTS OF VIBRATION.

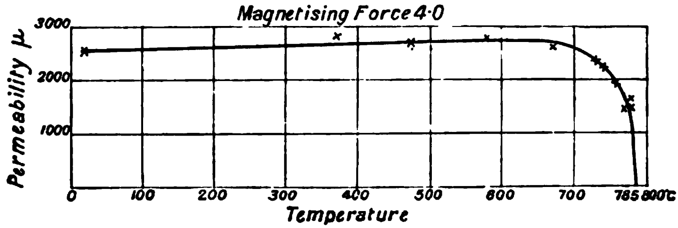
The effects of vibration on magnetism are to diminish all residual actions, and to cause the specimen more rapidly to assume the mean state corresponding to the magnetic force present. If a specimen of soft iron is examined while under rapid vibration, it is found that in it there is scarcely any difference between the ascending and descending curves of magnetization. A single tap on a wire of soft iron will at once destroy any residual magnetism in it.

EFFECTS OF HEAT.

When iron is warmed, its magnetic properties undergo singular changes. Rise of temperature produces different effects at different stages of the magnetization, and the effects differ in different materials. In soft iron, in weak magnetic fields, the effect of raising the temperature is to produce an increase of permeability, which goes on until the specimen is at a full red heat, about 760° C., when it reaches the enormous value of 10,000, after which point it suddenly falls, and when the temperature of 780° C. (about) is reached, the iron ceases to be a magnetic body, its permeability at that temperature, and at all higher temperatures, not differing sensibly from that of air or vacuum. But if placed in a very strong magnetic field, the action of raising the temperature produces a diminution of permeability, at first slight, then more rapid until the temperature of 780° C. is reached, when again all magnetism disappears. In steel, the effect is curiously different. In both soft and hard steels, the effect, in a very weak magnetic field of about $\mathsf{H} = 0{\cdot}2$, of raising the temperature is to increase the permeability, until it is heated to a point close up to 700° C., when it suddenly drops to zero. In a field of about $\mathsf{H} = 2$, its magnetization at the lower temperatures is greater, and the final drop sets in at a temperature considerably below 700°. In a strong field of $\mathsf{H} = 40$, the permeability drops steadily as the temperature rises. At high temperatures, too, all residual effects are smaller.

Fig. 100 shows the effects of temperature in modifying the magnetic curve of soft iron when under a magnetising force of H = 4. It will be seen that the permeability increases gradually, as the temperature rises, from about 2500 to 3000, at a temperature of 630°, after which it drops to unity at a temperature of 785° C.

FIG. 100.



EFFECT OF HEAT ON PERMEABILITY OF SOFT IRON.

RESIDUAL MAGNETISM.

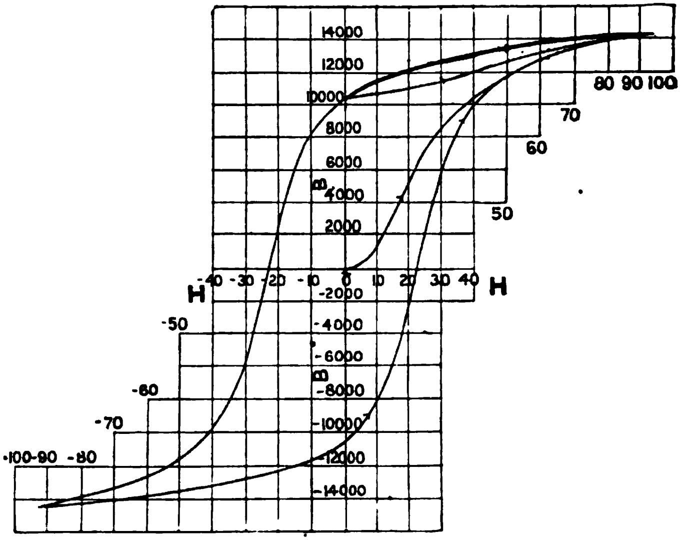
It is well known that several kinds of magnetic materials —lodestone, steel, particularly hardened steel, and hard sorts of iron—exhibit residual magnetism after having been subjected to magnetic forces. It is also known that closed circuits of soft iron—even of the very softest—will exhibit a considerable amount of residual magnetism so long as the circuit which they constitute is unbroken. A very simple illustration of this is afforded by any electromagnet possessing in its core and well-fitting armature a compact magnetic circuit. If it is excited by passing a current, which is then quietly turned off, the armature usually does not drop off, and may even require considerable force to detach it; but when once so detached will not again adhere, the residual magnetization not being permanent. In like manner a steel horse-shoe magnet, if magnetized powerfully while its keeper is across its poles, may become "supersaturated"; that is to say, magnetized to a higher degree of magnetization than it can retain in permanence, a portion of this residual magnetization disappearing the first time the keeper is removed. All these residual phenomena are part of a wide subject of magnetic after-effects. Owing to causes presently to be discussed, magnetic forces, if sufficiently powerful, produce effects on the molecules of a magnetizable body which remain after the cause has passed away, with the result that if the causes change in a continuous manner the effects also change in a continuous manner, but suffer a retardation in phase, the cause lagging after the effect. This must not be confused with an alleged time-lag of magnetism to which many things have been supposed to be due which were really due to quite other things. The present considerations relate to retardations in phase rather than in time, and occur no matter whether the operations themselves are conducted quickly or slowly.

Reference to Fig. 92 will show that when the magnetizing force H is gradually increased from zero to a high value, and is then gradually decreased to zero, the resulting internal magnetization B first increases to a maximum, and then decreases, but does not come back to zero. The curve descending from the maximum does not coincide with the ascending curve. In fact, when the magnetizing force has been entirely removed there remained (in this specimen) a residual magnetization of about 47,000 lines to the sq. in., or about 7300 lines per sq. cm. It has been proposed to give the name of the *remanence* to the number of lines per sq. cm. that thus remain as the residual value of B. To remove this *remanence*, a negative magnetizing force must be applied. Suppose enough magnetizing force has been used, the curve will descend and cut the horizontal axis at a point to the left of the origin; and with greater negative magnetizing forces, the specimen will begin to be magnetized with magnetic lines running through it in the reversed direction. The particular value of the negative magnetizing force which is needed to bring the remanent magnetization to zero has been termed by Hopkinson *the coercive force.* In the specimen of wrought iron in question the coercive force (in C.G.S. measure) is about 2, or in sq. in. measure about 13. The force thus required to deprive any specimen of its remanent magnetization may be taken as a measure of the tendency of iron of this particular quality to retain permanent magnetism. Hard kinds of iron and steel always show more coercive force than soft kinds of iron. For example, whilst that of soft wrought iron is about 2, that of hard steel may be as much as 50.

HYSTERESIS.

Professor Ewing, who has particularly studied the residual effects exhibited by various qualities of iron and steel, has given the name of *hysteresis* to this tendency of the effects to lag, in phase, behind the causes that produce them. The appropriate mode of studying hysteresis is to subject the specimen to a complete cycle (or to a number of successive cycles) of magnetizing forces. For example, let the magnetizing force begin at zero, and increase to a high value (say to H = 200) and then decrease back to zero, then reverse and increase to a high negative value, and finally return to zero. Such a cycle is given in Fig. 101, which is taken from Ewing's

FIG. 101.



CYCLE OF MAGNETIC OPERATIONS ON ANNEALED STEEL WIRE.

researches, and relates to a series of experiments made with a piece of annealed steel pianoforte wire. The curve begins in the centre of the diagram, and as H is increased positively, the curve rises at first concavely to the right, then turns over, and when $H = 90$ B has risen to a little over 14,000. When H is then reduced back to zero the curve turns back on itself, but does not fall as fast as it previously rose, for when H is reduced to 20, B has gone down only to 12,000, and when $H = 0$ the remanence is about 10,500. If at this point H had been again increased to 90, B would have run up again to 14,000, as shown by the thin line. If, however, the magnetizing force is reversed, the curve descends to the left, and cuts the horizontal axis at -24, which is therefore the value of the coercive force. On increasing the reversed magnetising force to $H = -90$, the reversed magnetization increases to the value $B = -14{,}000$, or a little more. Then when these reversed magnetizing forces are reduced to zero, the curve returns towards the right, crossing the vertical axis at $B = -10{,}500$ (the negative remanence); and on re-reversing the magnetizing force it is found that when $H = +24$, the magnetization is once more zero. After this point, increasing H causes the magnetization to run up very rapidly, not quite following its former track, but coming up as before to the apex, when H is raised to the same maximum of 90.

CYCLES OF MAGNETIZATION.

Such cycles of magnetization as that which has just been described, if carried out on any specimen of iron or steel, always yield curves that exhibit, like Fig. 48, an enclosed area. This fact has been shown by Warburg[1] and by Ewing[2] to possess a special significance, for the area inclosed is a measure of the work wasted in carrying the iron through a complete cycle of magnetizations. Just as the area traced out on the indicator-card of a steam engine is a measure of the heat transformed into useful work in the cycle of operations performed by the engine, so in this magnetic cycle the area enclosed by the curve is a measure of the work transformed into (useless) heat.[1]

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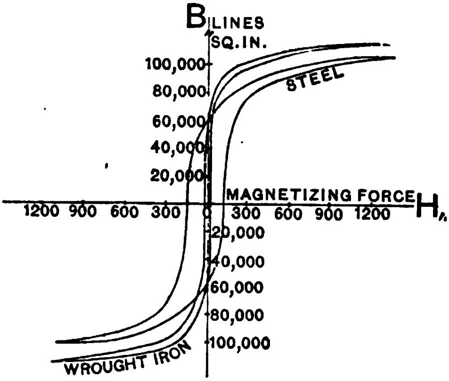
[1] *Wied. Ann.*, xiii. 141, 1881.

[2] *Proc. Roy. Soc.*, xxxi. 22, 1881; xxxiv. 39, 1884; and xxxv. 1, 1885; and *Phil. Trans.*, pt. ii. 523, 1885.

For the sake of comparison, a curve for wrought iron and one for steel are given side by side in Fig. 102. In all these

FIG. 102.



HYSTERESIS IN WROUGHT IRON AND IN STEEL.

cases the closed area represents the work which has been wasted or dissipated in subjecting the iron to these alternate magnetizing forces. In very soft iron, where the ascending and descending curves are close together, the enclosed area is small; and as a matter of fact, very little energy is dissipated in a cycle of magnetic operations. On the other hand, with hard iron, and particularly with steel, there is a great width between the curves, and there is great waste of energy.

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[1] The proofs of these matters are as follows. In a magnetic field of strength H it will require H units of work to move a unit of magnetism along a length of 1 centimetre against the magnetizing forces. Hence, since there are 4π magnetic lines to each unit of magnetism, the work done in one complete cycle on a single cubic centimetre of the iron will be equal to $\frac{1}{4\pi}\int H\,dB$. If H and B are in C.G.S. units, the work will be given in ergs per cubic centimetre. Hence if this number is multiplied by the number of cycles per second and divided by 10^7, the result will express the number of watts of power wasted.

Hysteresis may be regarded as a sort of internal or molecular magnetic friction, by reason of which alternate magnetizations cause the iron to grow hot. Hence the importance of understanding this curious effect, in view of the construction of electromagnets that are to be used with rapidly alternating currents. The following figures of Table IX. give the number of watts (1 watt = $\frac{1}{746}$ of a horse-power) wasted by hysteresis in well-laminated soft wrought iron when subjected to a succession of rapid cycles of magnetization.

TABLE IX.—WASTE OF POWER BY HYSTERESIS.

B	$B_{''}$	Watts wasted per cubic foot at 10 cycles per second.	Watts wasted per cubic foot at 100 cycles per second.
4,000	25,800	40	400
5,000	32,250	47·5	575
6,000	38,700	75	750
7,000	45,150	92·5	925
8,000	51,600	111	1,110
10,000	64,500	156	1,560
12,000	77,400	206	2,060
14,000	90,300	262	2,620
16,000	103,200	324	3,240
17,000	109,650	394	3,940
18,000	116,100	487	4,870

It will be noted that the waste of energy increases as the magnetization is pushed higher and higher in a disproportionate degree, the waste when B is 18,000 being six times that when B is 6000. In the case of hard iron or of steel the heat waste would be far greater.

Hopkinson has made the remark that the area $\int H\, dB$ is approximately equal to a rectangle, the height of which is double the remanence, and the breadth of which is double the coercive force.

Ewing has given the following values of the energy wasted in a magnetic cycle of strong magnetization on various brands of iron and steel:—

TABLE X.—WASTE OF ENERGY BY HYSTERESIS.

Brand experimented upon.	Ergs per cubic centimetre lost in one complete cycle of magnetisation.
Very soft annealed iron	9,300
Less soft " "	16,300
Hard drawn iron wire	60,000
Annealed steel wire	70,500
Glass hard steel wire	76,000
Pianoforte steel wire (ordinary state)	116,000
" " " (annealed)	94,000
" " " (glass hard	117,000

These figures are surpassed by some of the brands examined by Hopkinson, who found that oil-hardened tungsten steel, the sort chosen for making permanent magnets because of its great coercive force, wasted no less than 216,864 ergs per cubic centimetre per cycle.

Ewing has shown that vibration tends to destroy residual effects. Also Dr. Finzi has found[1] that iron cores whilst traversed by an alternating electric current show no hysteresis, the ascending and descending curves of magnetization coinciding. There is also some evidence that with very rapid frequencies there is less work wasted per cycle than there would be in the same cycle performed slowly.

When an armature core is rotated in a strong magnetic field the magnetization of the iron is being continually carried through a cycle, but in a manner quite different from that in which it is carried when the magnetizing force is periodically reversed, as in the core of a transformer. Mordey has found[2] the losses by hysteresis to be somewhat smaller in the former case than in the latter.

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[1] *The Electrician*, xxvi. 72, April 3, 1891.

[2] See also Ewing, in *Electrician*, xxvii. 602, 1891.

MAGNETIC CREEPING.

Another kind of after-effect was discovered by Ewing, and named by him "viscous hysteresis." This is the name given to the gradual creeping up of the magnetization when a magnetic force is applied with absolute steadiness to a piece of iron. This gradual creeping up may go on for half-an-hour or more, and amount to several per cent. of the total magnetization. This is a true, but slow, magnetic lag, and must not be confounded either with the lag of phase discussed already under the name hysteresis, or with the apparent lag due to the retardation of the magnetizing current resulting from self-induction, or with the apparent lag observable in unlaminated iron cores due to eddy-currents circulating in the mass of the iron itself.

FORMULÆ FOR THE LAW OF THE ELECTROMAGNET.

Many attempts have been made to find a working formula to express the amount of magnetism which is produced in a given electromagnet by an exciting current of any particular value. Of these an elaborate account is given in the second and third editions of this book. As these are not founded on the principle of the magnetic circuit, they fail to account for all the various facts. And as they are not used in dynamo designing, they may be very briefly dismissed. They all amount to attempts to find a formula to represent algebraically the curves of magnetization such as that given in Fig. 92, p. 140.

The earliest suggestion of Lenz and Jacobi was a simple proportion between the exciting current (or ampere-turns) and the magnetism produced. This is equivalent to saying that the curve of magnetization is a straight line sloping upwards from the origin. Joule showed that this law was not true; that with sufficient magnetizing power saturation set in. Müller (followed by Von Waltenhofen, Kapp, and others) proposed an arc-tangent formula; suggesting that if the exciting current be represented by the length of a straight line drawn as a tangent to a circle, then the arc which it subtends will represent the amount of magnetism which results. This gives a saturation limit (for when the tangent is infinitely long the arc attains a finite value), but fails to represent the facts in the earlier stages of magnetization. Lamont, from theoretical considerations, proposed an exponential formula, from which he deduced an approximate expression

$$m = \frac{\mathrm{M}kx}{1 + kx},$$

where m is the magnetism at any stage, M is its possible maximum value, x the exciting current, and k a constant depending on the units employed. This is equivalent to saying that the ratio of m to x (in other words, the permeability) is at all stages proportional to the defect of saturation $\mathrm{M} - m$.

Frölich's Formula.—Lamont's formula was revived by Frölich,[1] and largely used in various forms by various writers, including the author of this book. Let us make the supposition that the magnetic flux N will have at complete saturation a maximum value $\overline{\mathsf{N}}$, and that the magnetizability of the magnet at any stage is proportional to the room left for magnetic lines, that is to $\overline{\mathsf{N}} - \mathsf{N}$. Now, writing S for the number of spirals and i for the current flowing in them, we get $\mathrm{S}i$ for the ampere-turns of exciting power, and $\mathsf{N} \div \mathrm{S}i$ will be the ratio of magnetism to magnetizing power or magnetizability. We may then write

$$\frac{\mathsf{N}}{\mathrm{S}i} = \frac{\overline{\mathsf{N}} - \mathsf{N}}{h},$$

where h is a constant of the particular electromagnet, the nature of which will be shown presently. By simple transformation this equation becomes

$$\mathsf{N} = \overline{\mathsf{N}}\frac{\mathrm{S}i}{\mathrm{S}i + h},$$

and it is clear that the meaning of h is that particular number of ampere-turns which will reduce the magnetizability to half its initial value, or will bring up the magnetism to half-saturation.

This number of ampere-turns the author named the *diacritical* number, and the number producing half-saturation he called the *diacritical* current. Dr. Frölich has independently made use of this conception, and has applied it in his formula for dynamos. The argument is his; the notation here used is, however, the author's.

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[1] *Elektrotechnische Zeitschrift*, pp. 90, 139, 170, 1881, and p. 73, 1882.

Writing $(Si)'$ for the diacritical number of ampere-turns, we have $(Si)' = k$, whence

$$N = \overline{N} \frac{Si}{Si + (Si)'}.$$

But, further, if S is known, then we may cancel it out and write simply

$$N = \overline{N} \frac{i}{i + i'},$$

where i' is the diacritical or half-saturating current. This very simple equation is approximately true for every electromagnet excited by a single current. Two observations made on any electromagnet will suffice to determine the two constants $\overline{N}$ and i'. Further, if r be the resistance of the magnetizing coil, since $ir = e$ (the potential required to send the current i through the coil), we may obviously write the equation

$$N = \overline{N} \frac{e}{e + e'};$$

where e' is the diacritical difference of potential, namely, that difference of potential which, applied to the coil having resistance r and convolutions S, will half saturate the core. This last form is most convenient when calculations are to be made about shunt-dynamos, whilst the one preceding it is the more useful for series dynamos.

None of these formulæ account for the phenomenon alluded to on p. 141, which is observed in the magnetization of many pieces of iron and steel (and especially in closed rings of iron and steel), namely, that there is an apparent increase in the permeability after a certain early stage in the magnetization has been reached. Lenz first noticed this in 1854. Wiedemann, Dub, Stoletow, Rowland, Chwolson, Bosanquet, and Siemens have all investigated the matter; Rowland, Bosanquet, and Ewing in particular having given careful numerical determinations of the variations of permeability under varying degrees of ascending magnetization. The researches of Chwolson and of Siemens seem, however, to show that the apparent increase of the permeability is due to the want of homogeneity in the iron, and to the presence of a certain proportion of particles having the properties of hard steel and requiring a certain minimum of magnetizing force to be applied before they become sensibly magnetized, there being an apparent more rapid growth of the magnetism when this stage is reached. According to this view, the permeability due to temporary magnetism begins by being a maximum, and diminishes as the magnetizing force is increased; whilst the permeability due to permanent magnetism is zero at first and until a certain stage, when it rises rapidly to a maximum of its own, and thereafter dies gradually away. That which Stoletow, Rowland, and Bosanquet have measured with so much care, is the sum of these two effects. Siemens makes the valuable remark that the harder the piece of iron or steel, the later is the stage at which this apparent maximum of magnetic permeability is observed.

The result of this superposition of effects in the dynamo machine is that when the "characteristic" is taken *with ascending strengths of current*, there may be observed—and this is not marked, save in dynamos in which the iron constitutes very nearly a closed circuit on itself—a concavity, as explained on p. 141, in the first part of the characteristic, which is often taken as an oblique straight line. But if the characteristic is taken with descending strengths of current, no such concavity is observed, the magnetism of the field-magnets, and also the electromotive-force, having values considerably higher, for the same value of exciting current, than in the ascending curve. The presence of permanent magnetism in the core is therefore detrimental to the steadiness of the field. Even with the softest Swedish iron, differences may be observed in the electromotive-force, with the same speed and the same exciting current, before and after the exciting current has been increased to a high degree. For this reason the approximate formula known as Frölich's is good enough as a first approximation, though it does not take into account the presence of the apparent increase in permeability or the retardation of the apparent maximum in cores having greater coercivity. For further information on the differences between the ascending and descending curves of magnetism, the reader is referred to the researches of Warburg, Ewing, and Hopkinson, or to the summary of them in the earlier part of this chapter.

Ewing's Molecular Theory of Magnetism.—Ewing's recent theory of induced magnetism accounts for the observed effects, but does not lend itself to any simple formula. He has shown[1] that all the phenomena of hysteresis, remanence, influence of stress, heat, and the like, can be explained on the supposition that the individual molecules which act as elementary magnets are subjected to mutual directive actions. He supposes, with Weber, that the act of magnetization consists in turning these molecules into alignment with the magnetic force, complete saturation being attained when all have been completely turned round. The apparent increase in permeability when a certain value in the magnetizing force has been attained he explains by showing that at a certain stage an instability will be set up, when, with any small increase in the magnetizing force, a large number of the molecular magnets will suddenly swing round into new positions. He has further shown that in a model constructed with a large number of small pivoted magnets exercising mutual influences, the magnetic properties can be explained by considering the configurations assumed by the system under the joint action of external and internal magnetic forces. Mr. A. Hoopes[1] has verified Ewing's theory by studying the magnetic properties of such an assemblage of small pivoted needles acting as a whole, and finds the system to exhibit instabilities and hysteresial effects like those of masses of iron.

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[1] *Proc. Roy. Soc.*, June 19, 1890; also *The Electrician*, xxv. 514. 541.

Magnetic Reluctivity.—The reciprocal of magnetic permeability has been called reluctivity by Kennelly.[2] If this quantity is plotted out against H, the curve so plotted is nearly a straight line, or the reluctivity is a linear function of H of the form $a + b\,\mathsf{H}$. This oblique line is simply the reciprocal to the hyperbolic curves found by Stoletow and others for μ and H. As pointed out by Fleming,[3] and more recently by Kennelly, the circumstance that the reluctivity is found so nearly a linear function of H is a justification of the empirical formula of Frölich given above on p. 166.

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[1] *Electrical World*, xvii. 358, 1891.

[2] *Ibid.*, xviii. 350, 1891.

[3] *Journal Inst. Electrical Engineers*, xv. 570, 1886.

CHAPTER VII.

THE MAGNETIC CIRCUIT.

THE most important recent step in the practical treatment of magnetic problems has been the use of the conception of the magnetic circuit. The principle is briefly as follows: that *a minimum expenditure of magnetizing power will give a maximum of effective magnetism when the iron parts of the dynamo, the cores of the field-magnets, the yoke, the pole-pieces, and the core of the armature, are so disposed that they constitute together a magnetic circuit having a minimum magnetic reluctance.*

It is no novelty to regard the magnetism of a magnet as something that traverses or circulates around a definite path, flowing more freely through such substances as iron, than through other relatively non-magnetic materials. Analogies between the flow of electricity in an electrically-conducting circuit, and the passage of magnetic lines of force through circuits possessing magnetic conductivity are to be found abundantly in the literature of the science. So far back as 1821, Cumming[1] experimented on magnetic conductivity. The idea of a magnetic circuit was more or less familiar to Ritchie,[2] Sturgeon,[3] Dove,[4] Dub,[5] and De la Rive[6] the last-named of whom explicitly uses the phrase "a closed magnetic circuit." Joule[7] found the maximum power of an electromagnet to be proportional to "the least sectional area of the entire magnetic circuit," and he considered the resistance to induction as proportional to the length of the magnetic circuit. Faraday[1] considered that he had *proved* that each magnetic line of force constitutes a closed curve; that the path of these closed curves depended on the magnetic conductivity of the masses disposed in proximity; that the lines of magnetic force were strictly analogous to the lines of electric flow in an electric circuit. He spoke of a magnet surrounded by air being like unto a voltaic battery immersed in water or other electrolyte. He even saw the existence of a power, analogous to that of electromotive-force in electric circuits, though the name *magnetomotive-force* is of more recent origin. The same idea is more or less implicitly recognised in the latter half of the magnetic papers in Sir William Thomson's collected volume on Electrostatics and Magnetism. The notion of magnetic conductivity is to be found in Maxwell's great treatise (vol. ii. p. 51), but is only briefly mentioned. Rowland[2] in 1873 expressly adopted the reasoning and language of Faraday's method in the working out of some new results on magnetic permeability, and pointed out that the flow of magnetic lines of force through a bar could be subjected to exact calculation; the elementary law, he says, "is similar to the law of Ohm." Writing R for the "resistance to lines of force," M for "magnetizing force of helix," and Q for number of "lines of force in a bar at any point," he wrote, for a particular case (a ring-magnet, having therefore a closed magnetic circuit), the equation,

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[1] *Camb. Phil. Trans.*, April 2, 1821.

[2] *Phil. Mag.*, series iii. vol. iii. 122.

[3] *Ann. of Electr.*, xii. 217.

[4] *Pogg. Ann.*, xxix. 462, 1833. See also *Pogg. Ann.*, xliii. 517, 1838.

[5] *Dub. Elektromagnetismus*, p. 401 (ed. 1816); and *Pogg. Ann.*, xc. 440, 1853.

[6] De la Rive. *Treatise on Electricity* (Walker's translation), i. 292.

[7] *Ann. of Electr.*, iv. 59, 1839; v. 195, 1841; and *Scientific Papers*, pp. 8, 34, 35, 36.

$$\mathfrak{Q} = \frac{M}{R};$$

an equation for magnetic circuits which every electrician will recognise as being precisely like Ohm's law. He applied the calculations to determine the permeability of certain specimens of iron, steel, and nickel. In 1882,[1] and again in 1883, Mr. R. H. M. Bosanquet[2] brought out at greater length a similar argument, employing the extremely apt term "Magnetomotive Force," to connote the force tending to drive the magnetic lines of induction through the "magnetic resistance" or "reluctance" of the circuit. In these papers the calculations are reduced to a system, and deal not only with the specific properties of iron, but with problems arising out of the shape of the iron. Bosanquet shows how to calculate the several reluctances of the separate parts of the circuit, and then add them together to obtain the total reluctance of the magnetic circuit.

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[1] *Experimental Researches*, vol. iii. arts. 3117, 3228, 3230, 3260, 3271, 3276, 3294, and 3361.

[2] *Phil. Mag.*, series iv. vol. xlvi. August 1873. 'On Magnetic Permeability and the Maximum of Magnetism of Iron, Steel, and Nickel.'

Prior to this, however, the principle of the magnetic circuit had been seized upon by Lord Elphinstone and Mr. Vincent, who proposed to apply it in the construction of dynamo-electric machines. On two occasions[3] they communicated to the Royal Society the results of experiments to show that the same exciting current would evoke a larger amount of magnetism in a given iron structure, if that iron structure formed a closed magnetic circuit, than if it were otherwise disposed. They embodied their ideas in a form of dynamo,[4] which however, on account of mechanical difficulties, did not establish itself as a permanent type of machine. The work of Lord Elphinstone and Mr. Vincent was not however lost, for the principle thus introduced by them into the construction of dynamos took root and bore fruit. In June 1884, the author of this book, in the preface to its first edition, writing on the imperfection of our knowledge of the laws of magnetic induction wrote: *We want some new philosopher to do for the magnetic circuit what Dr. Ohm did for the voltaic circuit fifty years ago.* In the autumn of the same year, at the conference of electricians at Philadelphia, Professor Rowland read a paper[1] in which he proposed a formula for the number of magnetic lines in a field-magnet. He found the product of the existing current into the number of spirals in which it circulated (i.e. the ampere-turns) and divided this by a complex expression, representing the *resistance* to the flux of the magnetic lines in the air and in the iron; allowing something for the tendency of some of the magnetic lines to escape.

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[1] *Proc. Roy. Soc.*, xxxiv. 445, December 1882.

[2] *Phil. Mag.*, series v. vol. xv. 205, March 1883. 'On Magneto-motive Force.' Also *ibid.*, vol. xix. February 1885; and *Proc. Roy. Soc.*, No. 223, 1883. See also *Electrician*, xiv. 291, February 14th, 1885.

[3] *Proc. Roy. Soc.*, xxix. 292, 1879; and xxx. 287, 1880. See *Electrical Review*, viii. 134, 1880.

[4] Specifications of Patents, 332 of 1879, and 2893 of 1880. See also the former editions of this work.

An important development of the foregoing ideas was made by Mr. Gisbert Kapp, in a series of papers contributed to the *Electrician*[2] between February 1885 and April 1886 in which the question of the design of dynamos was discussed from this point of view, with many illustrations touching the forms of field-magnets, and some calculations and formulæ of great interest. While these papers were in progress, the author was preparing for the press the second edition of this work, and drew up the sketches of the magnetic circuits of a large number of types of dynamo machines, that are given in a collected form in Fig. 119. Three months later a sheet of figures, very closely resembling these, was given by Mr. Kapp, who had prepared them in entire independence, in an important paper[3] which he communicated on Nov. 24th, 1885, to the Institution of Civil Engineers. In this paper Kapp adopted a new unit of lines of force, 6000 times greater than the C.G.S. unit, the reason of this being that he preferred to have to divide by 10^6 instead of 10^8, and to speak of the number of revolutions per minute instead of the number of revolutions per second. Using Z for the number of magnetic lines, in Kapp units (where $Z = N$ of our notation C.G.S. units $\div$ 6000), and n for revolutions per minute, Kapp puts,

$$E \text{ (volts in armature)} = Z \cdot Nt \cdot n \cdot 10^6 ;$$

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[1] Report of the Electrical Conference at Philadelphia in 1884, p. 77. See also *Electrical Review*, xv. 368, 1884; and *Electrician*, xiii. 536, 1884.

[2] *Electrician*, xiv. 159, 307, 347, 390, 431, 511; xv. 23, 190, 250; xvi. 7, 406.

[3] *Proc. Inst. Civil Engineers*, lxxxiii. (1885–6), pt. 1, "Modern Continuous-Current Dynamo-Electric Machines and their Engines."

the symbol Nt standing for number of turns of wire around the armature as counted all round the periphery (the same for which symbol C is used in this book hereafter). Kapp then further wrote for the magnetic circuit the formula

$$Z = \frac{P}{R_a + R_A + R_F},$$

where P is the exciting power in ampere-turns, R_a the magnetic reluctance of the air-space, R_A that of the armature core, R_F that of the field-magnets. Now let δ represent distance across the span between armature core and polar surface, b breadth of armature as measured parallel to axis, λ the length of arc embraced by polar surface, so that $\lambda\, b$ is the polar area out of which magnetic lines issue, a radial depth of armature core, so that $a\, b$ is area of section of armature core (space actually occupied by iron only being reckoned), A B area of field-magnet core, l length of magnetic circuit within armature, L ditto in field-magnet; all the dimensions being measured in inches or square inches respectively. Then, in case of an ordinary single magnetic circuit, Kapp writes

$$R_a = 1440 \frac{2\,\delta}{\lambda\, b},$$

$$R_A = \frac{l}{ab},$$

$$R_F = 2 \frac{L}{A\,B},$$

The coefficient 1440 arises from the peculiar units, inch for length, minute for time, and 6000 C.G.S. for unit of magnetic lines; and this number may be taken as representing in this mixed system of units the specific magnetic reluctance of air. The coefficient 2 relates to the specific reluctance of wrought iron or charcoal iron; the figure 3 must be substituted in case of cast-iron magnets.[1] Moreover, on account of magnetic leakage in the formula for Z, 0·8 P has to be used instead of P. In the debate on this paper, Prof. G. Forbes gave a further modification of the formula. Still more recently Mr. Kapp[1] has returned to the subject, and has given an empirical rule for calculating the variations of the magnetic reluctance of the iron at the various stages of magnetism.

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[1] These formulæ are explained in *Electrician*, xv. 250, August 14th, 1885.

In May 1886, Drs. John and Edward Hopkinson communicated to the Royal Society[2] a very complete and elegant investigation of the problem of magnetic circuits, for the purpose of finding a suitable and accurate expression for the electromotive-force of the dynamo in terms of the magnetizing current; the most important part of their investigation being directed to constructing the curve characteristic of magnetization of the dynamo from the ordinary laws of magnetism and from the known properties of iron. The process in its first approximation resembles the process adopted by Kapp; but it stands alone in an important respect, namely, that its authors plot a separate characteristic curve for the relation between the magnetizing force and the induction for each separate part of the magnetic circuit, and then sum up the separate curves so as to obtain a final resultant characteristic curve. This is done first on the assumption that there is no magnetic leakage, and with other assumptions for the sake of simplifications. After a first approximation has thus been obtained, the theoretical result is compared with the actual result of experiment, thereby affording a means of estimating the corrections that must be introduced, the magnitude of the correcting factors being thus known, and the theory perfected to a second degree of approximation.

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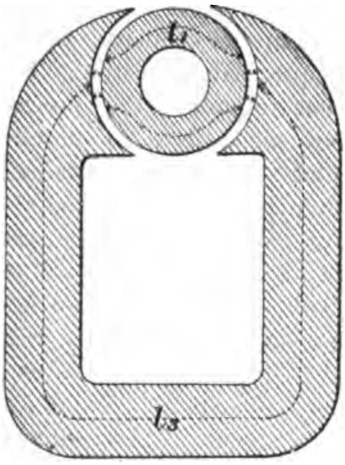
[1] *Journal Soc. Telegraph Engineers and Electricians*, xv. 524–529, November 11th, 1886. "On the Predetermination of the Characteristics of Dynamos"; a very valuable paper marred by mixed units. Those who wish to study examples of this mode of calculating, will find some examples in a paper communicated by Professor Jamieson in Jan. 1889 to the *Institution of Engineers and Shipbuilders in Scotland*; vide *Electrician*, March 1, 1889.

[2] *Phil. Trans.*, part i. p. 331, 1886. "Dynamo-Electric Machinery." This important paper is reprinted *in extenso*, but without the plates, in *Electrical Review*, xviii. 471, November 12th, 1886, and subsequent numbers. See also *Electrician*, xviii. 39, 63, 86, and 175, in issues of November 19th, November 26th, December 3rd, and December, 31st, 1886, where the figures of the plates are printed in the text.

In describing the Hopkinsons' formulæ, we shall employ not their notation, but the same that is adopted in the rest of this book (see p. 208).

Let N be the whole magnetic flux through the armature, that is to say, the total number of lines of magnetic force that pass into the armature core on one side and out of it at the other. Assume (to simplify matters) that there is no waste or leakage of magnetic lines. Then remember that the magneto-motive force (or line-integral of the magnetizing[1] forces acting round the circuit) is equal to 4 π S $i \div 10$, where S is the number of turns of wire and i the amperes. Now the magnetic reluctance of any magnetic conductor is proportional to its length and inversely proportional to its sectional area, and also inversely proportional to its permeability. Suppose then, as shown in Fig. 103, that the magnetic circuit of the dynamo is made up simply of three parts; an iron armature-core, the two air-gaps, and the iron field-magnets, then the iron armature-core, in which the average length of path for the magnetic lines is l_1, the average sectional area A_1, and of permeability μ_1, will have a magnetic reluctance equal to $\frac{l_1}{\mu_1 A_1}$. Similarly for the two gaps: if the length of path across each, from iron to iron, be called l_2, and the area of either polar surfaces be A_2, and the

FIG. 103.



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[1] See Maxwell's *Electricity and Magnetism*, vol. ii. art. 499; or S. P. Thompson's *Elementary Lessons on Electricity and Magnetism* (edition of 1887, pp. 291–296. See also p. 125 of this book.

permeability of the matter that occupies the gaps be called μ_2, then the magnetic reluctance these two offer to the magnetic flux will be $2\frac{l_2}{\mu_2 A_2}$; or, remembering that for air, copper, and all ordinary non-magnetic substances $\mu = 1$, this may be written simply $2\frac{l_2}{A_2}$. Similarly for the iron field-magnet; writing l_3 for length of path through the iron from pole to pole, A_3 for sectional area (supposed to be equal throughout), and μ_3 for permeability, the magnetic reluctance will be $\frac{l_3}{\mu_3 A_3}$. Adding these three reluctances together, we get as the total reluctance of the magnetic circuit the value

$$\frac{l_1}{\mu_1 A_1} + 2\frac{l_2}{A_2} + \frac{l_3}{\mu_3 A_3}.$$

Whence we may immediately write down as the appropriate formula,

$$\text{total number of magnetic lines} = \frac{\text{magneto motive-force}}{\text{magnetic reluctance}}; \text{ or}$$

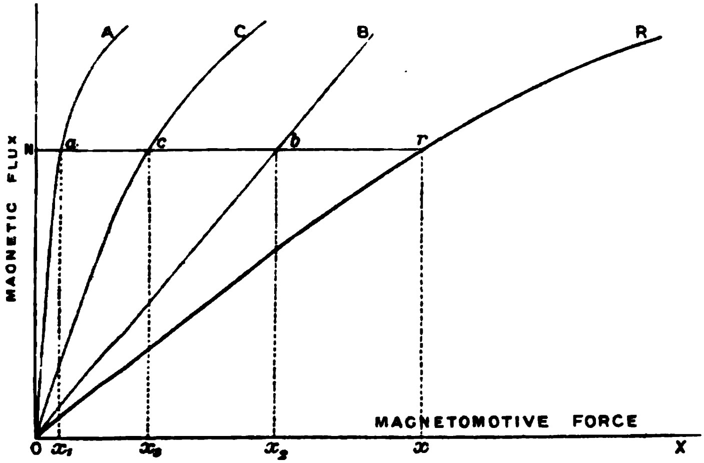
$$N = \frac{4\pi S i}{10\left\{\frac{l_1}{\mu_1 A_1} + 2\frac{l_2}{A_2} + \frac{l_3}{\mu_3 A_3}\right\}}$$

As a matter of fact, the Hopkinsons stated their formula a little more generally. In the first place, instead of adding up the separate magnetic reluctance, they calculated the magnetic forces needed in the separate parts and then added these together. In the second place, instead of assuming the existence of μ for the different parts, they contented themselves with saying that the magnetic induction in each part must be some function of the magnetic force acting in that part. Now, if there be a flux of N magnetic lines passing through sectional area A square centimetres, the number of lines per square centimetre, which we call the "*induction*" B, will be equal to $\frac{N}{A}$. Accordingly, we may write for the magnetomotive-force acting in the armature part of the magnetic circuit $f\left(\frac{N}{A_1}\right) \times l_1$, which "function" may be examined and plotted out as a curve. In fact the curves of magnetization, such as are given on p. 132, are nothing else than curves which show the relation between the magnetizing forces and the amount of magnetism they induce. There will be a similar expression $f\left(\frac{N}{A_3}\right) \times l_3$ for the magnetomotive-force that acts in the field-magnet part, whilst for the gaps the magnetomotive-force is simply $\frac{N}{A_2} \times 2\,l_2$; for the function for air = 1. Now, if we know the separate amounts of magnetizing force required to produce these magnetic inductions in the separate parts, it is clear that the whole or integral magnetizing force in question will be got by adding them together, giving

$$l_1 f\left(\frac{N}{A_1}\right) + 2\,l_2 \frac{N}{A_2} + l_3 f\left(\frac{N}{A_3}\right) = 4\,\pi\, Si \div 10.$$

There are three advantages in this mode of stating the matter :—(1) The use of the function of which the value is to be found by reference to a curve or tabulated set of observations (such as those given in Figs. 92, 93, and 95, or statistically on p. 146), instead of merely using the symbol μ, makes the expression more general; (2) the separate terms being differently affected by leakage of the magnetic lines, it is easy to apply a correction to any one of them separately; (3) this form of the formula is convenient, in the case of a given iron carcase, to calculate the number of ampere-turns required to excite the working quality of magnetism. For we have now three terms, the first telling us how many ampere-turns of excitation are required to drive N magnetic lines through the reluctance of the armature core, the second telling how many are required to drive N lines through the gap-space, and the third telling how many are required to drive N lines through the iron cores of the field-magnets. In a well-designed dynamo the second term is numerically the most important of the three, and it is not complicated by any question of saturation; for in air the magnetic induction is always proportional to the inducing magnetic force. To represent this graphically upon a diagram (Fig. 104), plot out as ordinates the numbers of magnetic lines that are forced round the circuit, and plot horizontally as abscissæ the corresponding values of the requisite magnetomotive-force $4\pi S i \div 10$. For the second term, which relates to the gaps, the relation will be represented simply by a sloping line such as O B. For example the number of magnetic lines N that are to be forced across the gap between the armature and field-magnets being represented to scale by the length of the line O N, the corresponding value of $2 l_2 \dfrac{N}{A_2}$, which is the corresponding part of the magnetomotive-force, when plotted out on the horizontal scale as O x_2, gives b as a point through which the line passes. Similarly we may construct a curve to represent the first term by the curve A; for if we know from experiments made on iron of the same kind as is used in the armature core the values of the function f (or, what comes to the same thing, the various corresponding values of μ_1) we can calculate the

FIG. 104.



value of the quantity $l_1 f\left(\frac{N}{A_1}\right)$ and set it off as O x_1, giving a as a point on this curve. Similarly the curve C is calculated point by point for the third term, by using knowledge derived from experiments made on iron of the same kind as is used in the field-magnets. Now, from these three curves A, B, and C, which represent the various values of the three terms on the left-hand side of the equation, we can at once get the resultant curve that is characteristic of the whole magnetic circuit of the dynamo. For if we draw a level line across at the point N, we know that the three overlapping lengths N a, N b, N c, (which are respectively equal to the three lengths O x_1, O x_2, and O x_3,) represent the three corresponding separate parts of the magnetomotive-force. Adding these three lengths together, we get O x or N r as the total magnetomotive-force; and this gives us r as a point on the resultant curve, which we may complete by finding other points in a similar way and sweeping the curved line O R through them. Having in this way built up a curve characteristic of the magnetization, the Hopkinsons then proceeded to correct it by considering the leakage. They found that in the dynamo experimented upon (an Edison-Hopkinson) only about three-fourths of the magnetic lines created in the field-magnet actually passed through the armature core, the rest leaking across either between the pole-pieces through the air or the bed-plate, or else turning back from the pole-pieces to the yoke at the top. Experiment gave the ratio of the magnetic flux at a point half way up the upright iron cores to the flux through the armature as 1·32. That is to say, in this particular type of machine, to force 100 lines through the armature core one will have to excite 132 in the field-magnet cores, and therefore will have to put on more magnetomotive-force accordingly. Let the symbol v stand[1] for this ratio. Then in the particular dynamo experimented on there was a yoke at the top through which the length of (curved) path was l_4, and which had cross-section A_4. There were also solid pole-pieces, for which the corresponding quantities were called l_5 and A_5. Inserting these additional matters into the equation, it now becomes

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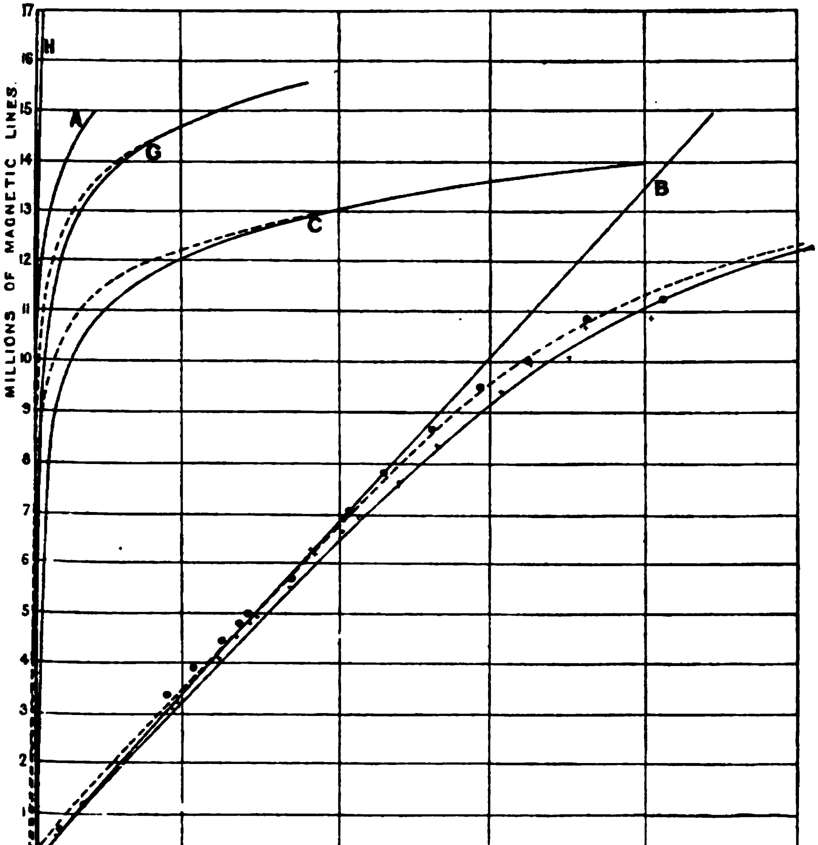
[1] It can be determined experimentally, or calculated as hereafter shown.

$$l_1 f\left(\frac{N}{A_1}\right) + 2 l_2 \frac{N}{A_2} + l_3 f\left(\frac{vN}{A_3}\right) + l_4 f\left(\frac{vN}{A_4}\right) + 2 l_5 f\left(\frac{N}{A_5}\right)$$
$$= 4 \pi S i \div 10.$$

FIG. 105.



There are now five terms to be calculated giving five curves. Moreover, as is well known, with descending magnetizing forces the curve of magnetization is different from the curve with ascending magnetizing forces. Fig. 105, which is taken from the Hopkinsons' paper, shows how they plotted out both for ascending and descending magnetizations the five curves. Of these, A relates to the armature, B to the two interstitial gaps, C to the field-magnet cores, G to the yoke, and H to the two pole-pieces. The resultant ascending and descending curves are also shown. They agree remarkably well with the crosses and points which were plotted out from actual experiment. The dotted curves and the crosses surrounded with circles relate to descending magnetization. The student should not fail to consult the original paper, which though brief is full of important matter, and in which applications of this method to two dynamos of different types are given.

The magnetization curves, Figs. 95 and 96, pp. 144 and 145, being the same used by the Hopkinsons, may be used by the student. The ordinates being values of $N \div A$, the abscissæ give the corresponding values of $f\ (N \div A)$ or of $\frac{1}{\mu}(N \div A)$.

Example.—In one particular machine examined by the Hopkinsons, the same Edison-Hopkinson dynamo described on p. 521, Figs. 351, 352, the following were the dimensions :—l_1 13 centimetres, l_2 1·5 centimetre, l_3 91·4 centimetres, l_4 49 centimetres, l_5 11 centimetres; A_1 810 square centimetres; A_2 on core 1410, on polar face 1513 square centimetres, or, allowing for spreading, say 1600 square centimetres; A_3 930 square centimetres; A_4 1120 square centimetres; A_5^3 1230 square centimetres; $v = 1·32$; N, when the machine was at full work, a little over 10,850,000; $S = 3260$; $r_a = 16·93$.

LEAKAGE OF MAGNETIC LINES.

In all dynamos there is some magnetic leakage. That is to say, in all dynamos, of the magnetic lines which are excited in the field-magnet some fail to pass through the armature, and leak out sideways, constituting a *stray field.* In some cases more than half the magnetic lines are wasted in leakage.

The ratio of total field to useful field is known as the coefficient of leakage v. Esson[1] has given the following values in sundry machines.

STRAY FIELD IN DIFFERENT DYNAMOS.

Name of Machine.	Field.	Armature.	Remarks.	Value of v.
Edison-Hopkinson	Single Magnet, 2-pole	Drum	Poles next bed-plate	1·32
Siemens	Single Magnet, 2-pole	Drum	Yoke next bed-plate	1·30
Phœnix	Single Magnet, 2-pole (Fig. 8)	Long Ring	Yoke next bed-plate	1·32
Phœnix	Double Magnet, 2-pole (Fig. 3)	Long Ring	Horizontal	1·40
Manchester	Double Magnet, 2-pole	Long Ring	Bed and one pole cast together	1·49
Victoria	Double Magnet, 4-pole	Short Ring	Ordinary pattern	1·40
Ferranti	Double Magnet, multipolar	Coreless Disk	Ordinary pattern (alternating)	2·00

The nature of leakage may be better comprehended by remembering that air is really a magnetic conductor, though less permeable than iron. The stray field around a dynamo may be explored by moving a compass-needle about in it; and the intensity at various points may be estimated by an exploring-coil connected to a suitable galvanometer. Fig. 106 depicts the general direction of the magnetic lines that leak from an Edison-Hopkinson dynamo. It will be noted that leakage takes place in other ways than from pole to pole. There will be a tendency to leak between any two points of the magnetic system between which there is a difference of magnetic potential. Thus, there is a tendency for magnetic lines to leak from the pole-pieces to the yoke at the top. The cast-iron bed-plate being in proximity to the two poles (where the difference of magnetic potential is greatest) promotes leakage through itself, even though the machine is mounted on a zinc footstep.

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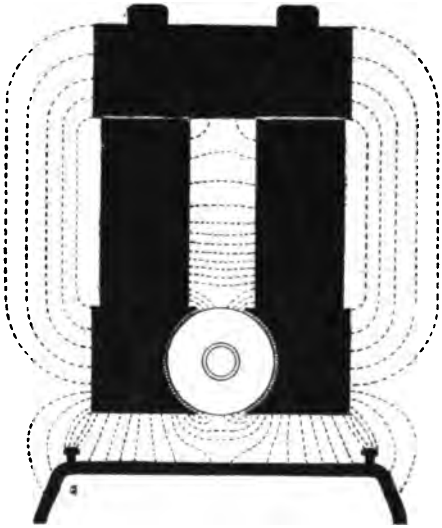
[1] *Journal Inst. Electrical Engineers*, xix. 122, 1890.

Many machines have been examined as to their magnetic leakage by Carl Hering,[1] who also has given drawings of them. An extraordinary case was found to be afforded by the stray field of the Thomson-Houston arc lighting dynamo (Fig. 307, p. 465). The reader should also refer to some experiments by Carhart[2] and to some by Trotter.[3]

FIG. 106.



STRAY FIELD OF AN EDISON-HOPKINSON DYNAMO.

It is evident that the leakage coefficient cannot be constant in a given machine, for the amount of leakage depends on the relative permeance of the path through the armature core and of the stray paths outside. Now the permeability of air is a constant, whilst that of the iron cores decreases as the degree of saturation is raised; so that the leakage increases with higher excitation. Also when a large current is drawn from the armature, the demagnetizing reaction of the armature current directly promotes leakage, as it raises an opposing magnetomotive-force in the direct path of the magnetic lines. Moreover, since leakage is not confined to actual polar ends, but takes place more or less all over a magnet, it is clear that what we call the coefficient of leakage is only a sort of average quantity.

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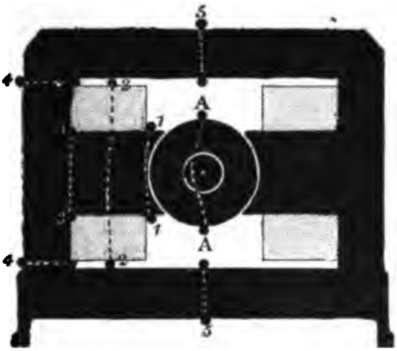
[1] *Electrical Review*, xxi. 186 and 205, 1887.

[2] *Electrical Review*, xxv. 286; and *Electrician*, xxiii. 644, 1889.

[3] *Journal Inst. Electrical Engineers*, xix. 243, 1890.

By experiment we may determine the actual value of the leakage ratio in various parts. Drs. J. and E. Hopkinson did this for a "Manchester" dynamo,[1] using exploring coils placed around the field-magnet of the dynamo in various positions. The number of magnetic lines which were thus enclosed was ascertained by suddenly cutting off the exciting current and noticing the resulting induction current in a suitable galvanometer. A still more complete examination was made by Lahmeyer[2] on an iron-clad dynamo (Fig. 107). In this case six separate exploring coils, each having the same number of turns, were used. That surrounding the armature, enclosing the useful field, is called A, the others being numbered. The deflexions obtained are given in column 2 of the following table. The maximum flux was found at 3. Taking this number as 100, the percentages of leakage at the coils are given in column 3. In column 4 are given the various fluxes, taking that through A as 100, and in column 5 the values of v at the various parts. It is clear that the yoke parts were of insufficient thickness.

FIG. 107.



EXPLORING THE MAGNETIC LEAKAGE OF A DYNAMO.

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[1] See their paper in *Phil. Trans.*, Part i. p. 331, 1886; and *Electrician*, xviii pp. 39, 63, 86, and 175, Nov. and Dec. 1886.

[2] *Elektrotechnische Zeitschrift*, ix. 283, 1887.

A	780	10·9	100	1
I.	788·5	10·1	101	1·01
II.	861	1·6	110	1·10
III.	876	0	112	1·12
IV.	850	3·0	109	1·09
V.	749	14·5	96	0·96

In the case of the Edison-Hopkinson dynamo, the Hopkinsons give 1·32 for v, this being the ratio observed between the throw when the exploring coil was placed half way up the magnet limbs and when it was placed around the armature. There is no doubt that the number is too small. If the exploring coil had been placed higher up, and if the armature had been excited so as to exert a demagnetizing action, the leakage coefficient would have been found to be at least 1·4.

CALCULATION OF LEAKAGES.

It is possible to predetermine, from the working-drawings of a dynamo before it is built, the probable amount of leakage. Calculations of the leakage are based upon the principle that where a circuit offers alternative paths, the magnetic flux will divide itself between the paths in the proportion of their relative facility for flow, exactly as an electric current divides where there are alternative conducting paths. In fact, the law of shunts has been found to hold good for magnetic lines. The reader should consult the researches of Ayrton and Perry[1] on this point. It follows that along any branched path the joint *permeance*[2] (or magnetic conductance) will be the sum of the permeances of the separate paths. Hence, if the permeances of the separate paths of the useful and waste magnetic fluxes of a dynamo are known, the coefficient of allowance for leakage, v, can be calculated, it being the ratio of the total flux to the useful flux. Call the useful flux u and the waste flux w; then

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[1] *Journal Soc. Teleg. Engineers and Electricians*, p. 530, 1886.

[2] *Permeance* is of course the reciprocal of magnetic reluctance; just as in electricity conductance is the reciprocal of electric resistance.

$$v = \frac{u + w}{u}$$

But each of these is a complex quantity; therefore the more complete formula is

$$v = \frac{u_1 + u_2 + u_3 + \; . \; . \; . \; . + w_1 + w_2 + w_3 + \; . \; . \; .}{u_1 + u_2 + u_3 + \; . \; . \; . \; .}$$

In order to determine the separate permeances along the various leakage paths, we must resort to some useful rules or lemmas originally suggested by Professor Forbes,[1] which consist in certain approximate integrations. For the convenience of British engineers the values have been recalculated into inch measures instead of centimetre measures, and other rules have been added.

Rule I.—Permeance between two parallel areas facing one another. Assume (Fig. 108) that the magnetic lines are straight and equally distributed over the surfaces: then,

Permeance $= 3 \cdot 1918 \times$ mean area (square inches) $\div$ distance (inches) between them

$$= 1 \cdot 596 \times (A_1'' + A_2'') \div d''$$

FIG. 108.

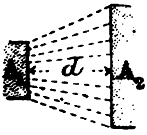
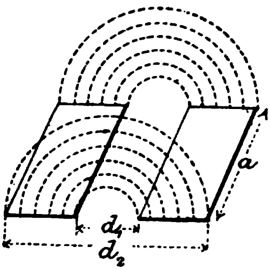


FIG. 109.



Rule II.—Permeance between two equal adjacent rectangular areas lying in one plane. Assuming (Fig. 109) lines of leakage to be semicircles, and that distances d_1'' and d_2'' between their nearest and furthest edges respectively are given; also a'' their width along the parallel edge:—

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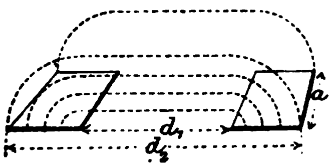
[1] *Journal Soc. Teleg. Engineers*, xv. 551, 1886.

$$\text{Permeance} = 2 \cdot 274 \times a'' \times \log_{10} \frac{d_2'}{d_1''}$$

FIG. 110.



Rule. III.—Permeance between two equal parallel rectangular areas lying in one plane at some distance apart. Assume (Fig. 110) lines of leakage to be quadrants joined by straight lines.

$$\text{Permeance} = 2 \cdot 274 \times a'' \times \log_{10} \left\{ 1 + \frac{\pi(d_2'' - d_1'')}{d_1''} \right\}$$

Rule IV.—Permeance between two equal areas at right-angles to one another.

Permeance = double the respective values calculated by II.

If measures are given in centimetres these rules become the following:—

I. $\frac{1}{2}(A_1 + A_2) \div d.$

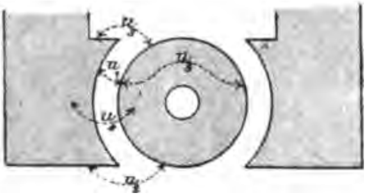
II. $\frac{a}{\pi}$ hyp. log $\frac{d_2}{d_1}$

III. $\frac{a}{\pi}$ hyp. log $\left(1 + \frac{\pi\,(d_2 - d_1)}{d_1}\right)$

Using these rules Mr. Ravenshaw has developed them for the calculation of dynamos for Messrs. W. T. Goolden & Co. Applying them to predetermine the leakage to fly-wheels, pedestals, and shafts, he is thus able to predict the performance of a machine, from the working drawings, to within 2 per cent.

EXAMPLE OF LEAKAGE CALCULATIONS.

FIG. 111.



It is required to predetermine the coefficient of leakage of the Edison-Hopkinson dynamo described on p. 521 (Fig. 353), the dimensions of which are given on p. 413. This is the same machine the stray field of which is depicted in Fig. 106, p. 184.

We must first determine the items which go to make up the useful permeance *u*, then those which make up the waste permeance *w*; having found these calculate *v*. But since the permeance of the useful flux depends on the permeability of the iron core of the armature, it will be needful to calculate the value of *u* at several different stages of saturation.

Now the items of *u* are five in number, and must be evaluated separately.

u_1 *Permeance of one Gap-space* (by Rule I.).

$u_1 = 3{\cdot}1918$ ½ (radius of core + radius of pole-piece) × 2π × $\frac{\text{angle of pole face}}{360}$ × length of pole-piece parallel to shaft ÷ distance from core to polar face,

$$= 3{\cdot}1918 \times (4{\cdot}812 + 5{\cdot}406) \times 3{\cdot}1416 \times \frac{129}{360} \times 19 \div \frac{19}{32};$$

whence

$u_1 = 1176.$

u_2 *Permeance into armature below poles* (Fig. 112).

Assume under surface is plane and apply Rule II.

$$u_2 = 2{\cdot}274 \times 19 \times \log \frac{5}{1};$$

$$= 2{\cdot}274 \times 19 \times 0{\cdot}703$$

whence

$u_2 = 29.$

u_3 *Permeance into armature above, from limb* (Fig 113).

FIG. 112.

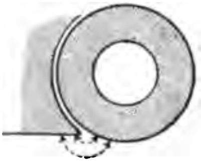


FIG. 113.

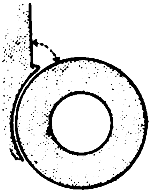


FIG. 114.

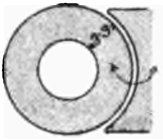
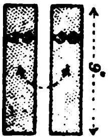


FIG. 115.



This is taken as twice u_2, since path of lines is half as long.

$u_3 = 58.$

u_4 *Permeance from flank of pole-piece to flank of armature core* (Fig. 114).

Apply Rule II. on assumption that these two areas (Fig. 114) act like two rectangles 9 inches long, 3·3 inches wide, and ¼ inch apart (Fig. 115).

$$u_4 = 2·274 \times 9 \times \log \frac{3·3}{0·25}$$
$$= 2·274 \times 9 \times 1·206$$
$$u_4 = 24.$$

u_5 *Permeance of iron of armature through core.*

Assume average length of path from side to side to be 5⅛ inches. It is needful to make three calculations, assuming three separate degrees of saturation of the core. Formula will be the reciprocal of that for the reluctance on p. 410.

[*a*] Core unsaturated: assume $\mu = 3000$.

$$u_5 = 3·1918 \times \frac{A\,\mu}{l};$$
$$= 3·1918 \times 125 \times 3000 \div 5·125;$$
$$u_5 = 233{,}550 \text{ (when unsaturated)}.$$

[*b*] Core saturated up to $\mathsf{N} = 10{,}850{,}000$; or $\mathsf{B}_{\prime\prime} = 87000$; whence

by Table II., p. 146, $\mu = 900$. This corresponds to degree of excitation when machine is at full load (see p. 182).

$u_5 = 3{\cdot}1918 \times 125 \times 900 \div 5{\cdot}125$;
$u_5 = 70065$ (at full load).

[*c*] Core saturated, as in more recent machines to $B_{''} = 110{,}000$; whence by Table II., p. 146, $\mu = 160$.

$u_5 = 3{\cdot}1918 \times 125 \times 160 \div 5{\cdot}125$;
$u_5 = 12456$ (at high saturation).

u Nett Useful Permeance.

Referring back to Fig. 111, we now see that the u_1, u_2, u_3, and u_4 are all in parallel with one another, and may be added; but that u_5 is in series with their sum, on each side; hence the nett permeance will be:—

$$u = \text{reciprocal of} \left\{ \frac{2}{u_1 + u_2 + u_3 + u_4} + \frac{1}{u_5} \right\};$$

and $u_1 + u_2 + u_3 + u_4 = 1287$.

Now take successively the three values found for u_5 and calculate u. This gives:—

[*a*] (core unsaturated)	$u = 642{\cdot}2$
[*b*] (core at full load)	$u = 638{\cdot}1$
[*c*] (core saturated highly)	$u = 612{\cdot}4$

Next calculate the *waste field.*

w_1 *Permeance to bed-plate* (Fig. 106, p. 184).

This will be half the permeance under one pole-piece; and must be calculated by Rule I., assuming area of top of bed-plate.

$w_1 = \frac{1}{2} \times 3{\cdot}1918 \times \frac{1}{2}$ (area under pole + area of $\frac{1}{2}$ top of bed-plate $\div$ width of the gap between them.

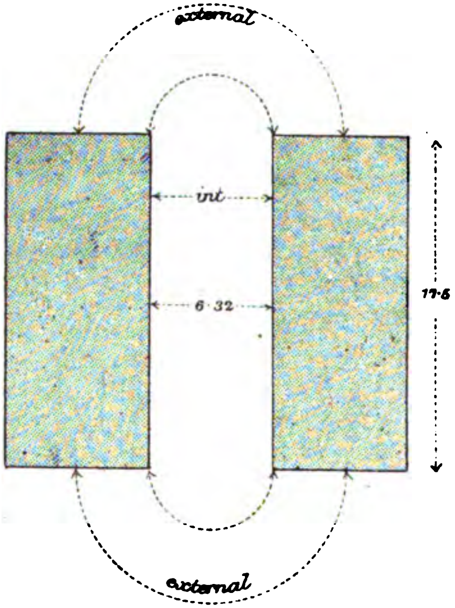
$= \frac{1}{2} \times 3{\cdot}1918 \times \frac{1}{2} (171 + 495) \div 5$

$w_1 = 106.$

w_2 *Permeance across limbs* (Fig. 116).

This consists of two parts, one external, one internal, they are calculated separately and added. *Internal part:* Calculate by Rule I.,

FIG. 116.



but adding a breadth equal to radius of smallest arc, owing to spread of magnetic lines.

$$= 3{\cdot}1918 \times \tfrac{1}{2}\left(17\tfrac{1}{2} + 23\tfrac{13}{16}\right) \times 18 \div 6\tfrac{5}{16}$$
$$= 188.$$

External part: Calculate one of the flanks by Rule II., and double

$$= 2{\cdot}274 \times 18 \times \log\left(23{\cdot}8 \div 6{\cdot}22\right) \times 2$$
$$= 47.$$

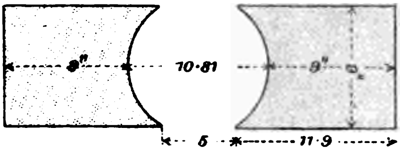
whence, adding the internal and external parts,

$$w_2 = 235.$$

w_3 *Permeance across flanks of pole-pieces.*

Treat these (as in Fig. 117) as blocks 9 inches high by 10 wide at a distance of 10·5 apart. Apply Rule II., and double.

FIG. 117.



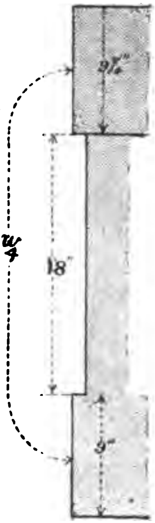
$$w_3 = 2\cdot274 \times 9 \times \log (30\cdot5 \div 10\cdot5) \times 2$$
$$w_3 = 19.$$

w_4 *Permeance from pole-pieces up to yoke* (Fig. 118).

Each pole-piece has three faces: imagine these spread out, to total breadth of 10 + 9 + 10 inches. Apply Rule III., and then take half because the two leakages are in series.

$$w_4 = 2\cdot274 \times 29 \times \log \left(1 + \frac{\pi \times 9}{18}\right) \div 2$$
$$= 14.$$

FIG. 118.



w *Nett permeance of stray field.*

Note that the leakages along the paths whose permeances are w_1, w_3, w_4, will be proportional to the difference of magnetic potential at the pole-pieces; but leakage along w_2 (between limbs), will be proportionately only half as great owing to fact that at upper end leakage is practically zero. Hence in adding up, take $\frac{1}{2}$ w_2 instead of w_2 itself.

$$w = w_1 + \tfrac{1}{2}\, w_2 + w_3 + w_4$$
$$w = 256\cdot5.$$

v *Final calculation of leakage coefficient.*

There are again three cases corresponding to the three values of u, to be calculated by the formula :—

$$v = \frac{u + w}{u}$$

[i.] When iron is quite unsaturated.

$v = (641{\cdot}7 + 256{\cdot}5) \div 641{\cdot}7$
$v = 1{\cdot}399.$

[ii.] Core working to full load.

$v = (637{\cdot}6 + 256{\cdot}5) \div 637{\cdot}6$
$v = 1{\cdot}402.$

[iii.] Core highly saturated.

$v = (611{\cdot}9 + 256{\cdot}5) \div 611{\cdot}9$
$v = 1{\cdot}419.$

These results justify the opinion that the number assumed by the Hopkinsons (1·32) for this machine was too small.

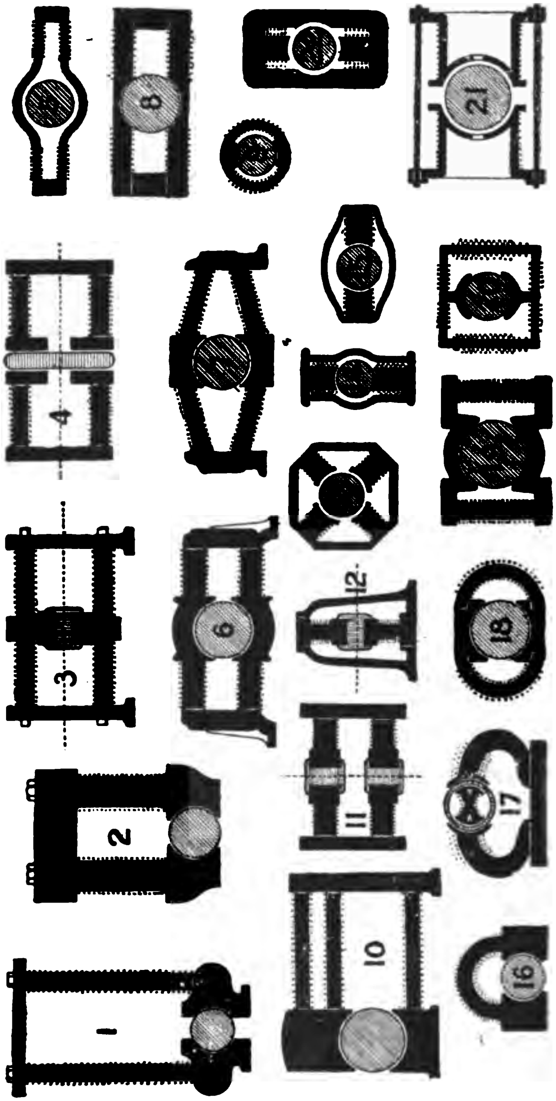
It may be noted in conclusion that the nett permeance of the waste field will, in a given type of machine, increase with both the length and diameter of the armature, being approximately proportional to the square root of the product of these two quantities. If two machines, built with the same size of core-disk, have armatures of different lengths, the machine with longer armature will have greater leakage permeance.

CHAPTER VIII.

FORMS OF FIELD-MAGNETS.

In Chapter III., on the elements of dynamos, something was said about the general principles which should be followed in the design of field-magnets. With the principle of the magnetic circuit to guide him, the reader will have little difficulty in judging of the relative value of the various designs; for he will remember that the magnetic circuit of highest permeability will have the most compact form, greatest cross-section, softest iron, and fewest joints. It has, moreover, been pointed out by Rowland that theoretically it is better that there should be one such magnetic circuit than that there should be two, though for practical structural reasons the author thinks the double circuit preferable in many cases. The double circuit, that is to say one resembling No. 3 or No. 8 of the accompanying Fig. 119, has in general the advantages that it affords a more stable framework, and that its magnetic field is generally more symmetrical than that of No. 2. These points should be borne in mind in considering the forms depicted in the accompanying figures. No. 1. of these illustrations shows the form adopted by Wilde for use with the shuttle-wound armature of Siemens. Two slabs of iron are connected at the top by a yoke, and are bolted below to two massive pole-pieces. There are four joints in the magnetic-circuit, in addition to the armature-gaps, and the yoke is insufficient. No. 2 shows the form adopted in the latest Edison dynamos (American pattern). The upright cores are stout cylinders. The yoke is of immense thickness; the pole-pieces are massive, but their lower corners are cut away. There are as many joints as in Wilde's form; but such a circuit would possess a far higher magnetic conductivity than Wilde's owing to the greater cross-section. One difficulty with such single circuit forms is how to mount them upon a suitable bed-plate. If mounted on a bed-plate

FIG. 119.



TYPICAL FORMS OF FIELD-MAGNETS.

of iron, a considerable fraction of the magnetism will be short-circuited away from the armature, as has been shown in the preceding chapter. In the larger form, No. 10, used at one time by Edison, this difficulty was only partially obviated by turning the magnets on one side.

A favourite type of field-magnet, having a double magnetic circuit with consequent poles, is represented in No. 3; it was introduced by Gramme. It may be looked upon as the combination of two such forms as No. 1, with common pole-pieces. Nos. 3 to 9 may be looked upon as modifications of a single fundamental idea. No. 4 gives the form used in the Brush dynamo (plan), the two magnetic circuits being separated by the ring armature. The diagram will serve equally for many forms of flat-ring machine; but in most of these the poles at the two flanks of the ring are joined by a common hollow pole-piece, embracing a portion of the periphery of the ring. No. 5 shows an early form of Siemens, with arched ribs of wrought iron, having consequent poles at the arch. The circuit is here of insufficient cross-section. No. 6 depicts a form adopted by Weston: and very similar forms have been used by Crompton, and by Paterson and Cooper. There is a better cross-section here. No. 7 is a form used by Burgin and Crompton, and differs but slightly from the last. It has one advantage—that the number of joints in the circuit is reduced. No. 8 is a form used by Crompton, Kapp, and by Paterson and Cooper. No. 9 is the form adopted in the little Griscom motor. No. 18 is a further modification due to Kapp. No. 19, which also has consequent poles, is used by McTighe, by Joel, and by Hopkinson ("Manchester" dynamo), by Clark, Muirhead & Co. ("Westminster" dynamo), by C. E. Brown (Oerlikon), by Blakey, Emmett & Co., and in some of Sprague's motors; but with slight differences in proportions of the details. The main difference between No. 19 and No. 6, lies in the position selected for placing the coils, No. 19 requiring two, No. 6 four. No. 20, which is a design of Elwell and Parker, is a further modification of No. 3, and would be improved by having a greater cross-section. In No. 3 (Gramme), it is usual to cast the pole-pieces and end-plates, but to use wrought iron for the longitudinal cores. The requisite polar surface must be got by some means, and when the core was made thin, the two courses open were either to fasten upon the core a massive pole-piece (Nos. 1, 3, 4, 6, 7, 19, 20), or else to arch the core No. 5 so that its lateral surface was available as a pole. Now, however, that it is known that massive cores are of advantage, the requisite polar surface can be obtained without adding any polar expansion or " piece," but by merely shaping the core to the requisite form (No. 8). This must not be regarded as a thinning of the magnet; for though mere reduction of cross-section at any part of the circuit would reduce the magnetic conductivity, reduction of the thickness for the purpose of bringing the armature more closely into the circuit will have quite the opposite effect. In fact the horizontal bars above and below the armature might be thinned away to nothing at their middle point, but for structural reasons. In all such forms of double magnetic circuit each half of the field-magnet may be regarded as having to furnish magnetic lines to its own half of the armature. Nos. 11 to 15 illustrate forms of field-magnet having *salient*, as distinguished from *consequent* poles. No. 11 is the double Gramme machine designed by Deprez. Nos. 12 and 13 are two of the innumerable patterns due to Gramme himself. These are both of cast iron; and it will be noticed that in No. 13 there are no joints, it being cast in one piece. No. 14 is the form used by Hochhausen, and is practically indentical with 21, save in the position of the axis of rotation. The iron flanks of number 14 tend to produce a certain short-circuiting of the magnetism by their proximity to the poles; and their sectional area is insufficient. No. 15, used by Van de Poele, is similar. No. 16 is the form used by the author in small motors, and is cast in one piece. The semicircular form adopted for the core was intended to reduce the magnet circuit to a minimum length. No. 17 illustrates the form used by Jürgensen, having salient poles reinforced by other electromagnets within the armature. No. 21 shows in section the double tubular magnets of the

Thomson-Houston dynamo, the spherical armature being placed, as in Nos. 12, 14, and 15, between two salient poles.

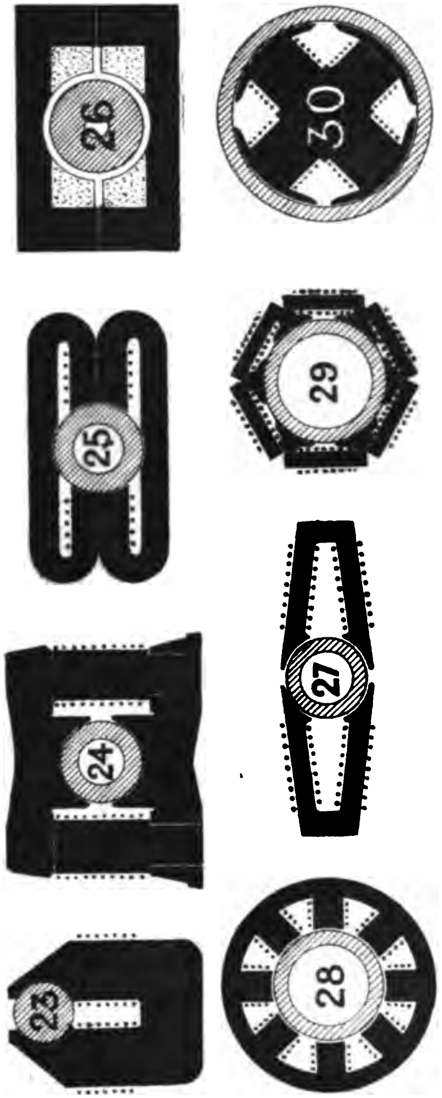


Fig. 120.

Typical Forms of Field-Magnets.

There is a curious analogy between Nos. 21 and 19; but they entirely differ in the position of the coils. No. 22 is a design by Kapp, in which there are two salient poles of similar polarity, and two consequent poles between them, one pair of coils sufficing to magnetize the whole quadruple circuit. Almost identical forms have been employed by Kennedy ("iron-clad" dynamo). Lahmeyer and Wenström employ iron-clad forms resembling No. 15. That of Wenström has for its yoke an external iron cylinder. No. 23, Fig. 120, is a type which, used long ago by Sawyer and by Lontin, has recently become a favourite one, having been revived almost simultaneously by Gramme ("type supérieur"), by Kapp, by Siemens ("F" type), by Cabella ("Technomasio"), and by Paterson and Cooper. No. 24 is Brown's very massive form. No. 25 is Kennedy's "iron-clad" dynamo: the iron cores are forged to shape. No. 26 is designed by Professor George Forbes. The ironwork is in two halves; the coils,

FIG. 121.

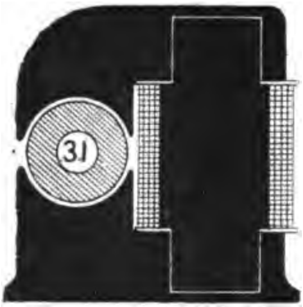


FIG. 123.

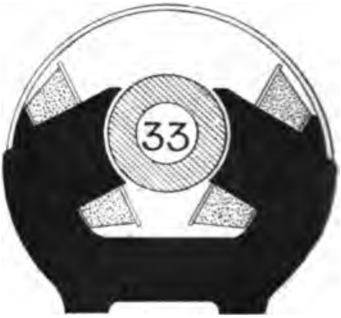
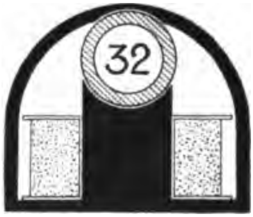


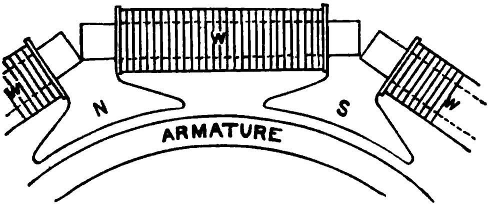
FIG. 122.



TYPICAL FORMS OF FIELD-MAGNETS.

which are entirely enclosed, are so placed as to magnetize the armature directly, one coil occupying all the available space between the field-magnet and the upper half of the armature; the other the similar space around the lower half. Eickemeyer, of Yonkers, uses a closely kindred form. No. 27 is the four-pole form adopted by Elwell and Parker in some of their larger machines. No. 28 is a multipolar form used by Wilde, Gramme, and others, the poles which surround the ring being alternately of opposite sign. It is now largely used for alternate-current machines such as those of Westinghouse (Stanley), Mather and Platt (Hopkinson), Paterson and Cooper (Esson), Elihu Thomson, Blakey and Emmott, and others. In No. 29, a modification of this design by Thury, for use with a drum armature, the six inwardly-directed poles are magnetized by coils wound upon the external hexagonal frame. This construction is shown in detail in Fig. 125. The cores which receive the windings are slabs of wrought iron, and are bolted to intermediate pole-pieces of cast iron. No. 30 is a sketch of a recent form adopted by Siemens and Halske, wherein an external ring rotates outside a very compact and substantial four-pole electromagnet. Similar machines have been designed by Ganz, Fein, and others, and are largely used in Germany for large central-station machines.

Fig. 125.

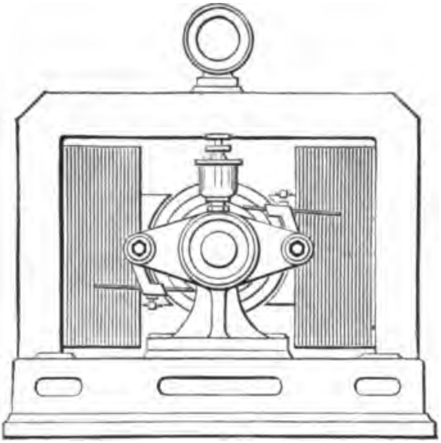


Detail of Thury's Field-magnet.

Another recent form of field-magnet is shown in No. 31. This, which is a single horse-shoe with but one coil upon it, was a design by the author of this work early in 1886: and a similar form was independently designed by Goolden and Trotter about the same time. One-coil machines have also been recently designed by Schorch, of Darmstadt, and by R. Kennedy, of Glasgow, by Immisch, and by J. G. Statter and Co. No. 32 represents also a machine requiring but one coil, and is of the iron-clad type. It was devised by McTighe in 1882, and has been recently revived by Stafford and Eaves. A recent pattern designed by Mordey for the Brush Company resembles No. 32, but has an external iron cylinder to enclose the coil. No. 33 represents the latest machine of Fein, of Stuttgardt, with inward-pointing poles.

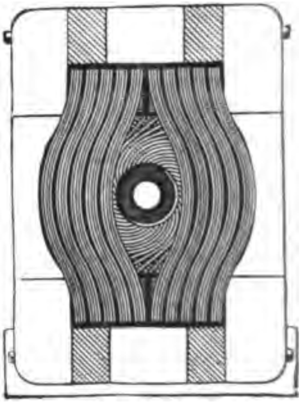
In Fig. 126 is represented Lahmeyer's form, also with inward-pointing poles. (See also Fig. 107, p. 185.)

FIG. 126.



LAHMEYER'S DYNAMO.

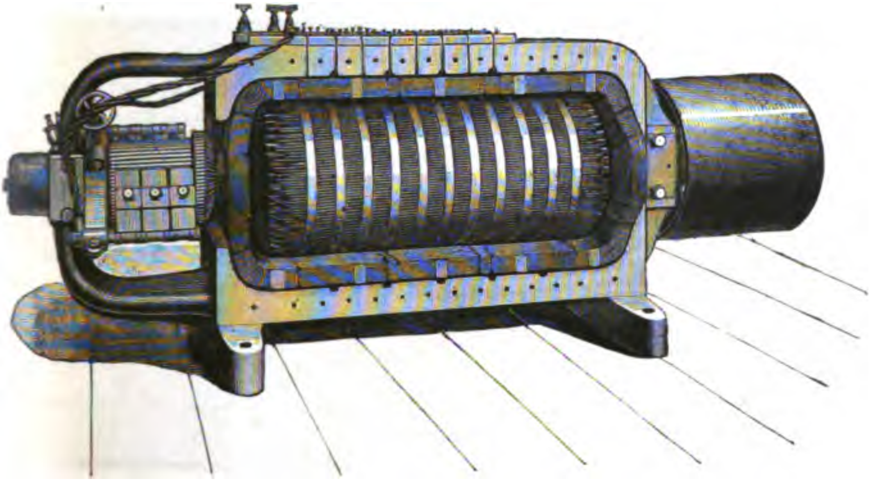
FIG. 127.



EICKEMEYER'S DYNAMO (showing coils).

Eickemeyer's dynamo (Fig. 127) realizes the suggestion of Forbes to place the magnetizing coils over the armature. The coils, which are separately wound on formers, fit into recesses between the upper and lower yokes and the inwardly projecting polar masses. Fig. 128 gives a view showing the interior disposition when one of the polar masses is removed. The defect of such forms is the difficulty of ventilating the closely enclosed armature.

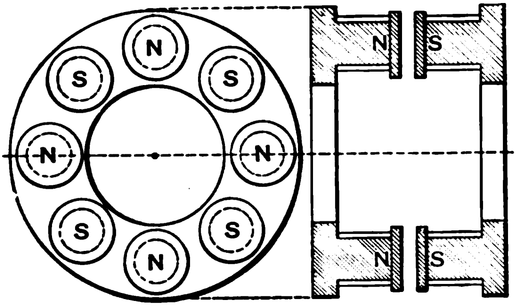
FIG. 128.



EICKEMEYER'S DYNAMO, WITH MAGNETIZING COILS SURROUNDING ARMATURE.

A typical form for alternate-current machines is that introduced by Wilde and used by Siemens, Gordon and

FIG. 129.

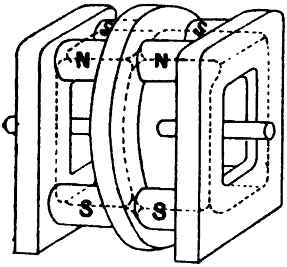


TYPICAL ALTERNATE-CURRENT FIELD-MAGNET.

Ferranti, having two crowns of alternate poles facing one another.

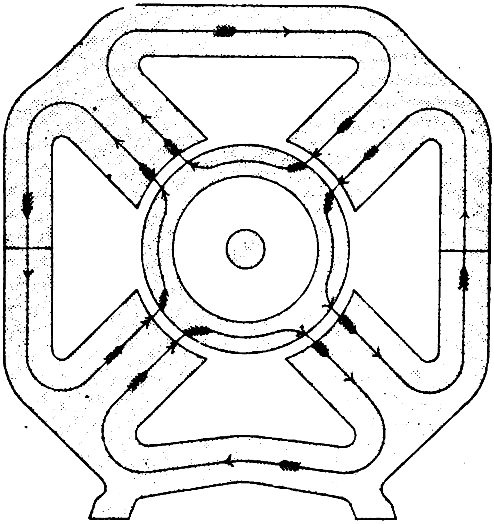
Fig. 130 represents a form of four-pole field-magnet used by the Brush Company for their Victoria (Mordey) machines, having double magnetic circuits and consequent poles. The cores to receive the coils are of wrought iron, whilst the end frames and pole-pieces are cast. This should be contrasted with the form of four-pole magnet used by Brown, of Oerlikon, in some large 300 horse-power machines for transmission of power. These are made entirely of cast iron, and have salient poles. The direction of the flux through these machines is indicated by dotted lines.

Fig. 130.



Four-pole Magnet (Mordey).

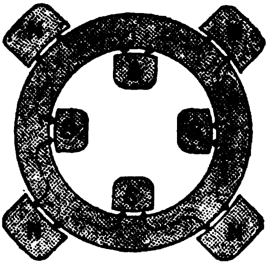
Fig. 131.



Four-pole Magnet (Brown).

The most notable departure in the forms of field-magnets in recent years is that due to Mordey, in whose alternator there is a field-magnet (see Plate XXI. Fig. 1), which, though it possesses but a single magnetic circuit with one exciting coil upon it, is nevertheless multipolar. This result is attained by the use of multiple pole-pieces which subdivide the magnetic flux into a number of separate magnetic fields. Another recent example of a multipolar machine (eight-pole) having a single magnetic circuit is afforded by the Edison Company's "marine" dynamo,[1] with a ring armature acted on by four internal and four external poles. The exciting coil lies behind the armature between the two sets of poles. The field-magnet of the three-phase alternator (Plate XXVIII.), designed by Brown for the transmission of power from Lauffen to Frankfort, is also of this improved kind, with a single exciting coil.

FIG. 132.



EDISON CO.'S MARINE DYNAMO.

Among such a multiplicity of designs one seeks for some indication as to the best. But the best for one purpose is not the best for all. Some designs are suitable for cast iron; others for wrought iron; others again, such as Figs. 121 and 130, are expressly intended to be composite, having wrought cores for the bobbins and cast polar masses. For small machines a simple circuit is probably the best. For large machines it is found needful to multiply the number of poles: and for alternators, multipolar forms are necessary for obtaining a sufficiently frequent alternation of currents.

Probably the future will see a general simplification of multipolar forms by the adoption of branched magnetic circuits.

In calculating those forms which have double or multiple magnetic circuits it is usual to simplify matters by considering one element of the whole, and making the calculations for it. Thus, for example, in Fig. 133, which depicts the half of such a machine as No. 8 of Fig. 119, it is sufficient to calculate the magnetic reluctances of half the machine in order to ascertain

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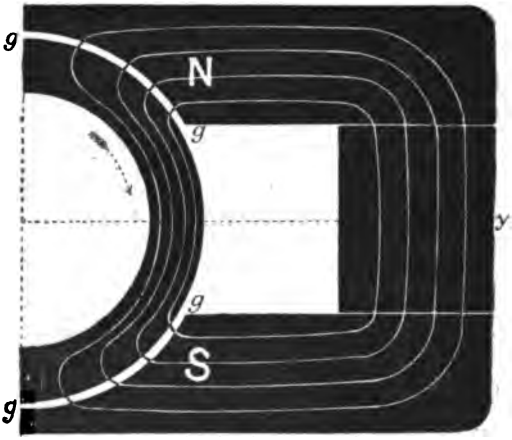
[1] *Electrical World*, xiii. 201, 1889; for a similar design by Mariotti, see *Electrician*, xxv. 139, 1890.

FIG. 133.



HALF OF A DOUBLE MAGNETIC CIRCUIT MACHINE.

the number of ampere-turns that must be wound upon it; a similar number being wound upon the other half. Forms with a double-magnetic circuit are preferable to those, such as Nos. 2, 23, and 31, with a single magnetic circuit, in all cases where there is likely to be much armature reaction. For in such forms as No. 23 the field is weaker under the two upper pole-tips than between the two lower ends of the pole-faces: in consequence, there is a powerful attraction downward of the armature. Further, because of this inequality of field the cross-magnetizing force of the armature will produce, in the single-magnet forms, an unsymmetrical distortion. As a consequence there is sure to be sparking at the brushes. For large-load armatures it is advisable not only to use double-magnets, but to separate their two halves by a distance-piece of brass.

CHAPTER IX.

ELEMENTARY THEORY OF THE DYNAMO. MAGNETO, AND SEPARATELY-EXCITED MACHINES. SERIES MACHINES. SHUNT MACHINES.

EXPERIENCE has shown that the main problems that require to be considered in the design of dynamos, are best solved by reference to the *magnetic circuit of the machine as a whole,* the iron core inside the armature being regarded as a constituent part of that circuit, and not as something which merely increases the effective area of the armature coils. In all that follows the armature is regarded merely as consisting of a certain number C of conductors, grouped in a particular way around an axis of rotation, their function being to cut across a certain actual number of magnetic lines that are furnished by the magnetic circuit. Also the symbol N stands, in the case of 2-pole machines, for *the whole number of lines of magnetic force that traverse the armature,* entering it on one side and again leaving it on the other; it is called by some writers the "total induction" through the armature, by others the "magnetic flux." For multipolar machines, N refers to any *one* of the separate magnetic circuits.

The number of revolutions *per second* made by the armature is denoted by the symbol n. It is found that the average electromotive-force generated by the armature is simply proportional to each of these quantities, so that by taking the appropriate units we may write, as will presently be seen, as the fundamental equation

$$\text{(average) } E = n\,C\,N \quad . \quad . \quad . \quad . \quad . \quad [\text{I.}]$$

In the earlier editions the field-magnet was regarded apart from the armature or its core, as having the function of creating a magnetic field; and the armature was regarded simply as a complex coil having a certain "effective area," rotating in that field. The average intensity of the field was denoted by the symbol H, and the equivalent effective area by A: the electromotive-force of the dynamo being proportional to the product of the two, and the speed n; or as it was written

$$\text{(average) } E = 4 n A H.$$

There was nothing incorrect in this way of regarding the matter; but neither A nor H were quantities that could be easily determined during the different stages of action of the machine. The iron core of the armature, in the present mode of treating the subject, is now regarded as having nothing to do with C, the armature factor, but as playing its part in the magnetic circuit in determining how many magnetic lines, namely N, shall be cut by the armature in its rotation. In brief, instead of trying to find an average *intensity*, we endeavour to think of the magnetic field as a whole—we endeavour to think of the *quantity* of it.

In the present chapter an expression is first found for the average electromotive-force, which expression serves as the fundamental equation of all dynamos. Then by introducing appropriate formulæ for the various circuits, equations are deduced for the various kinds of series-wound, shunt-wound, and compound-wound dynamos.

SYMBOLS USED.

It may be well to point out that in this and the succeeding chapters the following symbols are used in the following significations:—

A	area, expressed in *square centimetres.*
B	the magnetic induction, or number of magnetic lines per square centimetre.
b	number of external wires in a section of the armature.
β	angular breadth of a section of armature coil or of segment of collector.
C	number of conductors on the armature, counted all round the external periphery.
c	number of segments of collector or commutator.

E	entire electromotive-force generated in an armature,	expressed in *volts.*
ϵ	difference of potential from brush to brush,	
e	difference of potential from terminal to terminal,	
$\mathcal{E}$	electromotive-force of some external supply of electricity,	
η	economic coefficient, or efficiency (see pp. 234 and Chap. XXVIII.).	
F	force (i. e. push or pull), expressed in either *dynes*, *poundals*, *grammes'* weight, or *pounds'* weight.	
H	intensity of magnetic field (lines per sq. centim. *in air*).	
i	current in external circuit,	expressed in *amperes.*
i_a	current in armature,	
i_s	current in shunt coil,	
i_m	current in series coil of field-magnet,	
L	coefficient of self-induction.	
λ	average length of one turn of wire; also used for angle of lead.	
μ	coefficient of magnetic permeability of iron.	
N	whole number of magnetic lines that traverse a magnetic circuit.	
n	number of revolutions *per second.*	
ω	angular velocity (expressed in *radians*-per-second).	
p	number of *pairs* of poles.	
R	resistance of external circuit,	expressed in *ohms.*
r_a	resistance of armature coils,	
r_s	resistance of shunt coils,	
r_m	resistance of series coil on field-magnets,	
r	internal resistance of dynamo; equal to $r_a + r_m$ or to $r_a + r_s$ according to circumstances,	
ρ	resistance per unit of length,	
S	number of turns of wire in field-magnet coil in series with armature. Also, in general, for number of spirals.	
T	torque, or turning-moment, or angular force, or couple, or "effort statique," or "statisches Moment," expressed in *dyne-centimetres*, *gramme-centimetres*, *metre-kilogrammes*, or *pound-feet*, according to circumstances.	
T	is also used in the section on alternate-current dynamos for the periodic time of the alternating current, measured in *seconds.*	
t	time, measured in *seconds.*	
v	coefficient of allowance for magnetic leakage.	
W w	activity, or power, or work-per-second, expressed in *watts* or in *horse-power.*	
Z	number of turns of wire in shunt field-magnet coil.	

Wherever inch units are used instead of centimetre units, the marks already used on p. 142 will be employed for distinction.

FUNDAMENTAL EQUATION OF DYNAMO.

To find the average electromotive-force of a moving conductor, we must remember that, by definition, see page 20, this is (in absolute C.G.S. units) numerically equal to the number of magnetic lines that are cut in one second by the conductor. Also the practical unit, the *volt* being (see Appendix A) by definition equal to 10^8 absolute C.G.S. units of electromotive-force ; it will be necessary to divide the number of C.G.S. units by 10^8 in order to reduce the number to volts. Further, when there are, as in the armatures of dynamos, a number of conductors in series with one another, the total electromotive-force of the dynamo will be equal to the sum of the electromotive-forces of those conductors that are in series with one another. The fundamental equation will then be written :—

$$\text{(average) E (in } \textit{volts}\text{)} = n \, \mathrm{C} \, \mathrm{N} \div 10^8 \quad . \; . \; . \; . \; . \quad [\mathrm{I}a.]$$

We will deal first with an ordinary two-pole dynamo, having an armature in which the number of "sections" is denominated by the symbol c; the number of "segments" or "bars" in the commutator or collector will also be c. Let there be in each section b external wires or conductors, as counted on the outside of the armature core. (In ring-armatures there will be the same number of external wires as there are loops or windings in the section; in drum armatures there are twice as many external wires as there are loops or windings in the section). Then the number of external conductors or wires, reckoned all round the armature will be $b\,c$; it will be more convenient to use the single symbol C for this number. The number of external conductors or wires that are in series with one another electrically from brush to brush will be $\frac{b\,c}{2}$ or $\frac{1}{2}$ C. Now let the armature rotate with a speed of n revolutions per second. (Engineers usually count the revolutions made in one minute, necessitating division by 60 to get n.) Then one revolution will take $\frac{1}{n}$ part of 1 second.

We are now ready to calculate the electromotive-force.

No. of lines cut by 1 *external wire in* 1 *revolution* .. .. = 2 N;

(because each wire cuts all the lines where they go in at one side of the armature, and where they come out on the other).

No. of lines cut by 1 *external wire in* 1 *second* = $2\,n$ N;

No. of lines cut by ½ C *external wires in series in* 1 *second* .. .. = $2n \times \text{N}\,\tfrac{1}{2}\text{C}$;

No. of lines cut by ½ C *external wires in series in* 1 *second* .. .. = n C N.

Average electromotive-force (in C.G.S. units) = n C N;

Average electromotive-force (in *volts*) .. .. = $\dfrac{n\,\text{C N}}{10^8}$ . . [I*a*.]

It will be unnecessary in every case to write the divisor 10^8 in the formula, because it is easily remembered that, if omitted for the sake of brevity, the numbers obtained can be transformed at once to volts[1] by so dividing down.

For many purposes it is more convenient to have the fundamental equation in terms of the angular velocity. Let the symbol ω represent the angular velocity. Then

$$\omega = 2\,\pi\,n\,;$$

for, in each revolution, the angle described is $2\,\pi$ *radians* or 360 *degrees*. Consequently $n = \dfrac{\omega}{2\,\pi}$, which gives;

$$\text{(Average) E} = \frac{\omega}{2\,\pi}\,\text{C N} \;.\;.\;.\;.\;.\;.\;.\;.\quad [\text{I}b.]$$

It will be observed that this electromotive-force is simply an average; and it depends on the construction of the armature how much fluctuation there is in the value during a rotation.

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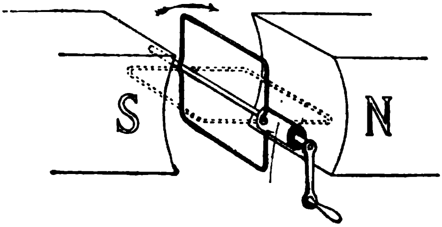
[1] Another way of lightening the formula would be to adopt as the unit quantity of magnetic flux, one hundred million lines, and in that case the symbol N would be used for the number of bundles of lines containing a hundred million each. But very few dynamos have been constructed in which the magnetic flux attained so great a quantity as one such bundle. The awkwardness of having the values of N always fractional would scarcely be compensated for in the gain of having a unit which fits so conveniently to the other practical international units. No difficulty is likely to arise from the omission of the divisor in the formulæ.

If, as in Fig. 134, the armature had but two external conductors forming a simple loop, then the electromotive-force would fluctuate between zero and a maximum. Calling the lowest point of the rotating loop in its vertical position 0°, then the position on the left of the dotted line will be 90°, if we reckon the angle of rotation in the clockwise direction. The top point will be 180°, and the point on the extreme right 270°. Then the induced electromotive-force will be zero as the coil passes through 0° and 180°, for at the positions 0° and 180° the conductors will be sliding along, rather than cutting, the magnetic lines, and a maximum as the coil passes through 90° and 270°. The *rate* of enclosing or "cutting" will be a *maximum* when the *actual number* of lines enclosed is a *minimum*, and *vice versâ*. (See p. 32.)

FIG. 134.



IDEAL SIMPLE DYNAMO.

At any intermediate angle, if the field is uniform, the actual number of lines of force enclosed is proportional to the cosine of the angle through which the coil has turned from its zero position, and the electromotive-force will be proportional to the sine of that angle. Strictly speaking, we ought to take the sine with a *negative* value to represent the electromotive-force, because as usually defined the induced electromotive-force is proportional to the rate of *decrease* in the number of lines of force enclosed. We need not, however, trouble about signs, because, if the commutator is properly set, all the induced electromotive-forces are thereby made to act in the same direction through the external circuit. The exact expression at any particular angle θ, for the electromotive-force of the loop may be calculated as follows:—The number of lines of force enclosed when the loop has turned through angle θ is $= \text{N} \cos \theta$; hence the rate of cutting will be ω N sin θ, or $2 \pi n \text{N} \sin \theta$. Now, since the average value of sin θ, between the limits $\theta = 0°$ and $\theta = 90°$, is $\frac{2}{\pi}$, the *average* electromotive-force *per loop* may be obtained by substituting this value, giving us

$$\text{Average E per loop} = 4\, n\, \text{N}.$$

And since the number of loops that are in series between brush and brush is $\frac{1}{2}$ C, we have finally

$$(\text{Average})\ \text{E} = n\, \text{C}\, \text{N}.$$

If the coil consisted of many turns all wound in one group, like the Siemens shuttle-wound armature, p. 33, the same expressions would obviously hold good on substituting the proper number for C.

Fluctuations of Electromotive-force in a One-coil Armature.

As explained above, the actual induced electromotive-force is proportional to the sine of the angle through which the coil has turned, or

$$\text{E} = 2 \pi n \text{N} \sin \theta \times \tfrac{1}{4}\, \text{C},$$

whence

$$\text{E} = \frac{\pi}{2} n\, \text{C}\, \text{N} \sin \theta \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad [\text{II.}]$$

As θ increases fron 0° to 360°, the value of the sine goes from 0 to 1, then from 1 to 0, from 0 to -1 and from -1 back to 0. The values of the sine are depicted in Fig. 135. The same curve may serve then to show how the electromotive-force would fluctuate if there were no commutator. But the action of the commutator is to commute the negative inductions into positive ones; the brushes being so arranged as to slide from one part of the commutator to the other at the moment when the inverse induction begins. This gives the curve the form of Fig. 136, which therefore represents how the voltage pulsates in the circuit of a simple old-fashioned shuttle-wound Siemens armature. Now if we could level these hills, and change our undulating induction into a steady one, we should get a single straight line, shown in Fig. 136 as a dotted line enclosing below it a rectangular area equal to the sum of the areas enclosed by the sinuous curves, and therefore at a height which is the average of the heights of all the points along the curves: in fact, since each sinuous curve is part of a curve of sines, the *average* height will be $\frac{2}{\pi}$, or about $\frac{7}{11}$ of the maximum height. In consequence of self-induction in the coils, the current will not actually fluctuate[1] as much as the voltage, the hollows being partly filled.

FIG. 135.

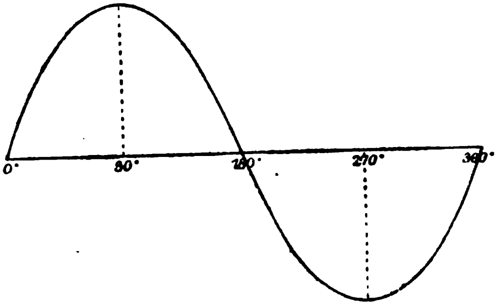
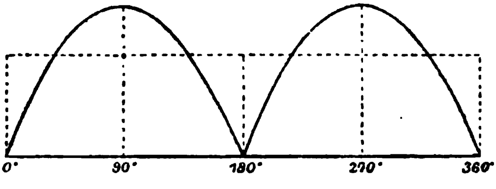


FIG. 136.



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[1] See remarks by Cromwell F. Varley in *Phil. Mag.*, 1867, and by Puluj in *Sitzungsber. Wien. Akad.*, II.*a*, May, 1891.

Fluctuations in a Closed-coil Armature divided into Sections.

As shown in the argument on pp. 40 and 41, it is, for reasons of construction, usual to wind armature coils in two sets connected in parallel. The two halves of the Pacinotti ring or the two halves of the windings on the Siemens drum meet at the brushes in parallel. If each of the two coils consisted of 100 turns, their joint effect in inducing electromotive-force would be no greater than that of either of them separately, but the internal resistance of the armature would be halved. From this point onwards in the argument it will be assumed that the armature windings consist of *pairs* of coils. Thus, instead of one coil of 200 turns, as shown in Fig. 137, we shall take it that there is a pair of coils each of 100 turns, as in Fig. 138.

FIG. 137.

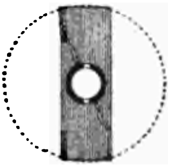


FIG. 138.

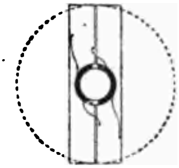
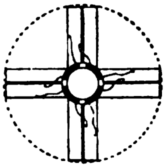
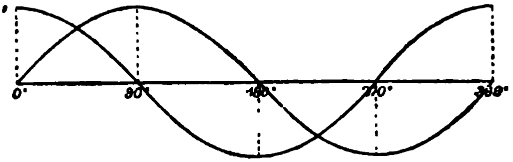


FIG. 139.



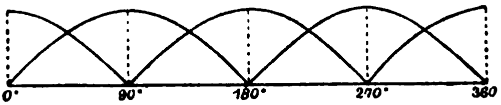
Now suppose that, in order to get a less fluctuating effect, we divide each of our original single pair of coils into two parts, and set these at right angles to one another. To take a numerical case, suppose there were originally 100 turns in each coil, and we split each into two coils of fifty turns, but set them across one another so that one comes into the best position in the field as the other is going out of it. (This arrangement is indicated in Fig. 139, which may be contrasted with Fig. 138 representing the undivided coil.) In this case we shall have two sets of overlapping curves—each of them will have to be but half as high as before, because the equivalent area of each coil is only half what it was for the whole coil. Then, if there were no commutator, the induced electromotive-force in the two sets of coils would fluctuate as shown by the two curves of Fig. 140. But if the ends of the two "sections" of the coil are joined to a proper commutator or collector, all the "inverse" inductions will be commuted into "direct" ones by the sliding of the brushes at the right moment, and

FIG. 140.



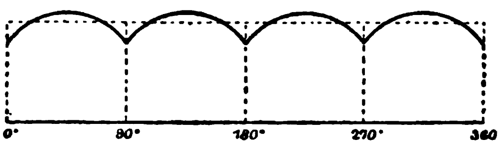
the two curves would then become as in Fig. 141. The next process is to ascertain what the joint result of these overlapping electromotive-forces will be: it is evident that from 0° and 90° the two inductive actions are assisting one another, and that at 45° they are equal. The nett result here is therefore double either of them; and, in fact, the

FIG. 141.



curve representing the *sum* of the two curves is given in Fig. 142. This curve shows at once a step towards *continuity*, as the fluctuations are far less than those of the single coil, Fig. 136. If, as before, we level the undulating tops by

FIG. 142.



a dotted line, we get precisely the same height as before. The *total* amount of induction (the total number of lines of force cut) is the same, and the *average* electromotive-force is the same. There is no gain, then, in the total electric work resulting from rearranging the armature coils in two sets at right angles to each other; but there is a real gain in the greater continuity and smoothness of the current.

If we again split our coils and arrange them as shown in Fig. 143 at angles of 45°, in four sets of pairs of coils of twenty-five turns each, and connect them up to a proper commutator, we shall get an effect which is very easily represented by constructing two curves, each similar to the last but each of half the height, and compounding them together (Fig. 144). One of them will of course have the maximum heights of crests occurring 45° further along than those of the other curve; and when these are compounded together we get for a resultant a curve shown in Fig. 145, which has exactly the same *average* height as before, but which has still less of fluctuation. It is easily conceived that this process of dividing the coil into sections, and spacing these sections out at equal angles symmetrically, would give us a result approaching as near as we choose to an absolutely continuous one. If our original pair of coils of 100 turns each were split into twenty sets of pairs of five turns each, or even into ten sets of pairs of ten turns each, the approach to continuity would be very nearly truly attained. It only remains to calculate the continuity algebraically; which, though not difficult, is rather tedious.

FIG. 143.

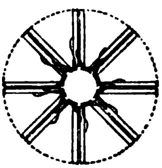


FIG. 144.

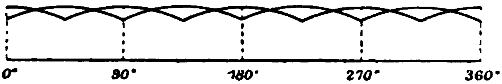
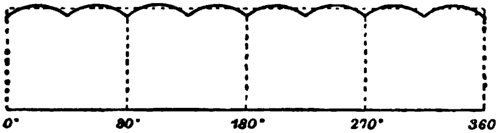


FIG. 145.



Calculation of Fluctuations of the Electromotive-force in Closed-coil Armatures.

We have seen in Chapter III. that in every armature a section the coil connected with any two commutator-bars is undergoin every instant an inductive effort exactly similar, but opposite in si to that going on in the section connected with the two bars on side of the commutator diametrically opposite. We likened the sets of coils in the two halves of the armature to two sets of galva cells arranged in parallel. Suppose the armature had in all thi six sections, then in reality there are two sets of eighteen, and electromotive-force induced in each set is alike. We will take case of a ring armature as being less complicated than the dr Let the symbol c stand for the total number of sections in the ar ture. There will be therefore $\frac{c}{2}$ sections in each half of the armat from brush to brush. Let each section consist of b turns of w The whole armature will consist of $b\,c$ turns. If these c sections set symmetrically round, the angle between the plane of each sec and the next one to it will be $\frac{360}{c}$ degrees or $\frac{2\pi}{c}$ radians. T may for some purposes be written $\frac{\pi}{\frac{1}{2}c}$; and for shortness we call this angle $= \beta$. We will then calculate the total electromot force induced in one set of sections, that is to say, in one of rows of $\frac{1}{2}c$ sections of coils extending half round the armature commutator from one brush to the other. Referring to and membering that only $\frac{1}{2}$ N lines, at most, go through any one sec at any instant, we see that in the first section, when it has tur through angle θ, the induced electromotive-force e_1, will be

$$e_1 = \omega \frac{N}{2} b \sin \theta,$$

where ω is the angular velocity. In the second section the elec motive-force will be

$$e_2 = \omega \frac{N}{2} b \sin(\theta + \beta),$$

because this section has a position differing by an angle β from first section. In the third section we have similarly

$$e_3 = \frac{N}{2} b \sin(\theta + 2\beta);$$

and so on, until we come to the last section of the set, for which the electromotive-force will be

$$e_k = \omega \frac{N}{2} b \sin\left(\theta + \overline{\tfrac{1}{2} c - 1}\, \beta\right).$$

But the whole electromotive-force of the set is the sum of all these separate electromotive-forces; so we have

$$E = \omega \frac{N}{2} b \times$$

$$\left\{ \sin\theta + \sin(\theta + \beta) + \sin(\theta + 2\beta) \ldots\ldots \sin(\theta + \overline{\tfrac{1}{2}c - 1}\, \beta) \right\}.$$

We can get, however, no information with respect to the maximum and minimum values of this fluctuating electromotive-force as long as the expression for E is in the form of a long series of values. We must proceed to sum this series within the brackets.

Inserting this value, we get at once

$$E = \omega \frac{N}{2} b \frac{\cos\left(\frac{\beta}{2} - \theta\right)}{\sin\frac{\beta}{2}}.$$

The amount of fluctuation implied in this formula depends on how the brushes are set. They slide, of course, from one bar of the commutator to another while the commutator moves through the angle β. So, if $\theta = 0$ at the beginning, when the commutator-bar is just beginning to touch the brush, then $\theta = \beta$ just as the bar leaves contact with the brush. And when the brush touches the middle of the bar $\theta = \frac{\beta}{2}$. Now the cosine is a maximum when the angle is a minimum. Therefore E will be a maximum when $\frac{\beta}{2} = \theta$, *i. e.* when $\frac{\beta}{2} - \theta = 0$: and E will be a minimum when either $\theta = 0$, or $\theta = \beta$. We have, consequently, the following results as the bar of the commutator passes under the brush:

(1) At beginning ($\theta = 0$),

$$E \text{ (a minimum)} \; \ldots\ldots = \omega \frac{N}{2} b \frac{\cos\frac{\beta}{2}}{\sin\frac{\beta}{2}}$$

$$- \omega \frac{N}{2} b \operatorname{cotan} \frac{90^\circ}{\frac{1}{2} c}.$$

(2) At middle of bar $\left(\theta = \frac{\beta}{2}\right)$,

E (a maximum) . . . $= \omega \frac{\mathrm{N}}{2} b \frac{1}{\sin\frac{\beta}{2}}$

$$= \omega \frac{\mathrm{N}}{2} b \operatorname{cosec} \frac{90^\circ}{\frac{1}{2}c}.$$

(3) At end $(\theta = \beta)$,

E (again a mininum) . . $= \omega \frac{\mathrm{N}}{2} b \frac{\cos\frac{\beta}{2}}{\sin\frac{\beta}{2}}$

$$= \omega \frac{\mathrm{N}}{2} b \operatorname{cotan} \frac{90^\circ}{\frac{1}{2}c}.$$

The greatest fluctuation therefore that can occur, will b difference between cosec $\frac{90^\circ}{\frac{1}{2}c}$ and cotan $\frac{90^\circ}{\frac{1}{2}c}$; and, since each as it passes under the brushes comes into the position just occu by the bar preceding it, there will be as many fluctuations in e revolution as there are bars in the commutator or sections in armature, namely *c*. Further than this, if we could increase number of sections indefinitely, so that $\frac{90^\circ}{\frac{1}{2}c}$ or $\frac{\beta}{2}$ was practically = then both cosec $\frac{90^\circ}{\frac{1}{2}c}$, and cotan $\frac{90^\circ}{\frac{1}{2}c}$ would be equal, and would equal to $\frac{c}{\pi}$; for $\frac{90^\circ}{\frac{1}{2}c} = \frac{\pi}{c}$, and for small angles the arc is sen equal to either the sine or the tangent. We will, however, calc the actual amount of fluctuation in certain cases. Many dyna are built with armatures having a 36-part collector, and thirt sections in the armature coil. We want to know the fluctuatio this case, and in other cases with fewer or more segments. following table gives the results of the calculations; the numbe sections of the armature and commutator being given in the column, and their angular breadth in the second. The fluctuati the difference between columns 3 and 4:—

c	β	$\frac{\operatorname{cosec}\frac{\beta}{2}}{c}$	$\frac{\cot\frac{\beta}{2}}{c}$	The Fluctuation.	Percentage Fluctuation.
2	180°	·5	0·	·5	±50·00
4	90	·3479	·2500	·0979	14·04
10	36	·3236	·3077	·0159	2·38
12	30	·3220	·3110	·0110	1·70
15	24	·3206	·3136	·0070	1·10
20	18	·3196	·3157	·0039	·61
24	15	·3192	·3165	·0027	·42
30	12	·3189	·3171	·0018	·28
36	10	·3187	·3175	·0012	·19
40	9	·3186	·3177	·0009	·14
45	8	·31857	·31780	·00077	·12
60	6	·31846	·31802	·00044	·07
90	4	·31838	·31819	·00019	·03
360	1	·31832	·31830	·00002	·003
5400	0° 4'	·3183099	·3183098	·0000001	·00001

From these figures it is apparent that the fluctuations become practically insignificant when the number of sections is increased; as indeed the curves of Figs. 136 to 145 showed. With a 20-part commutator the fluctuations of the electromotive-force in the armature are less than 1 per cent. of the whole electromotive-force. With a 36-part commutator, they are less than one-fifth of 1 per cent. So far as mere fluctuations are concerned then, it is practically a useless refinement to employ commutators of more than thirty-six parts. But there are other reasons, as we shall see in considering the self-induction in the separate sections, for making the number of sections as great as possible.

Now, assuming that we wind our coil in a large number of sections, so that the fluctuations may be negligible, what will the total electromotive-force be? We may write, as we have seen, $\frac{c}{\pi}$ for either cosec $\frac{\beta}{2}$ or for cotan $\frac{\beta}{2}$, giving us $E = \omega \frac{N}{2} b \frac{c}{\pi}$. Now $\omega = 2 \pi n$, and $b\,c$ = C, so that our formula once more becomes E = nC as before.

Measurement of Fluctuation.

The relative amount of fluctuation in the current furnished b dynamo may be observed by noticing the inductive effect on a nei bouring circuit. Let a coil be introduced into the circuit, and le second coil, wholly disconnected from the first, be laid coaxially w it, so that the coefficient of mutual induction between the coils sl be as great as possible. Introduce into the circuit of the second c a Bell telephone receiver. If the main-circuit current is steady th will be no sound heard. If it fluctuate, each fluctuation will indu a corresponding secondary current in the telephone circuit, and amount and frequency of the fluctuations may be estimated by loudness and pitch of the sound in the telephone. The fluctuati of the current of a Brush dynamo, which are about 1½ per cent., in this manner readily detected. Professor Ayrton has suggested introduction into the secondary induction circuit of an electro-dy mometer to serve as a " discontinuity-meter."

Effect of Non-simultaneous Commutation.

If the brushes are not so set that the sliding of contact under c brush is not accomplished at the same instant as that under the ot brush, then it is clear that there will be slightly unequal electromoti forces in the two halves of the armature circuit. This moment inequality will die out, to be succeeded by another inequality opposite sign) when commutation occurs at the other brush. T effect will be the same as though a small alternating current havi $2\,n\,c$ periods of alteration per second were made to act around t circuit of the armature. Such effects may be occasioned in armatu by various causes; if the number of sections in the armature be odd number; if the numbers of conductors in all the sections are n alike or their connexions are unsymmetrical; or lastly, if the conta edges of the brushes do not lie exactly at opposite ends of a diamet These effects are independent of a still smaller alternation arising every armature in consequence of mutual inductions between t currents in the commutated coils and those adjacent to them.

Measurement of N.

An important problem is how to measure the actual number magnetic lines that pass through the armature. This number really best ascertained by calculation from the performance of t machine itself. The speed being observed by aid of a suitable speed-counter, the number of conductors round the armature being known, and the whole electromotive-force generated in the machine being measured by proper electrical methods, then it only remains to apply the fundamental formula, transformed so as to calculate back to N :—

$$N = \frac{E \times 10^8}{nC}.$$

To measure E the means adopted must depend upon the construction of the machine. If it is a continuous-current machine, either magneto or separately-excited, then a simple voltmeter applied at the open terminals or brushes will suffice. If the machine is series-wound or shunt-wound, the same method may apply, provided the magnetizing coils can be disconnected and separately excited up (for example, by using accumulators) to the right degree while the machine is run. In all these cases the result will not correctly represent the working values, because in work there are the reactions due to considerable currents in the armature coils. To measure E while the machine is running, it must either be run upon known resistances (so as to enable E to be calculated from Ohm's law); or E may be calculated by measuring (see p. 228) the difference of potentials at the brushes with a voltmeter, and then calculating from the resistance of and current in the armature the volts lost internally, which, added to the measured volts, make up the whole E.

Another way, which does not involve the running of the machine —and is therefore less satisfactory—is to wind closely around the armature, exactly in the diameter of commutation, a single turn of fine insulated wire, the ends of which are connected through two insulated wires lying close together, or, better, twisted together, to a ballistic galvanometer of slow period and of appropriate sensitiveness. This being done, arrangements are then made to separately excite the field-magnets, by some auxiliary current, to an amount equal to the working value. On turning on the exciting current, a current of short duration, proportional in its integral value to the number of magnetic lines which have thus been introduced through the wire loop, is excited in the circuit and produces a throw on the galvanometer; the amount of this throw can be regulated by introducing suitable resistances. On breaking the exciting circuit or short-circuiting the exciting coils, another throw is observed in the opposite direction, and of equal amount. To ascertain the absolute number of lines indicated by this throw, a comparative experiment must be made with some sort of apparatus for introducing a known number of magnetic lines into the same circuit. A good way to do thi to use a hand-coil of large size (resembling on a large scale the of a tangent galvanometer), wound with a known number of turns fine wire, the average area of these turns being known from car measurement. Such a coil should be included in the circuit of aforesaid galvanometer, but with leading wires enabling it to placed at a sufficient distance away from the dynamo and from other magnets and iron, to allow of no error arising from such ca of perturbation. It should be laid level in some spot for which value of the vertical compound of the earth's magnetic field is kno (In London this is 0·43 C.G.S. units.) On suddenly inverting coil, another throw is produced in the ballistic galvanometer. result may be calculated out as follows:—Let δ_1 be the throw du introducing the N lines through the loop, and δ_2 the throw given inverting the coil. Calling the number of turns in the coil S, (average) area of each of them A, and V the intensity of the vert component of the earth's field, then the number of lines cut inverting the coil is 2 S A V. And N is found by solving the sim rule-of-four sum:—

$$N : 2\,S\,A\,V :: \delta_1 : \delta_2.$$

In a modification of this method, briefly described on p. Mr. Mordey measures in an alternator the number of magnetic l which pass at each position of the armature through its coils.

THE MAGNETO-MACHINE AND THE SEPARATELY-EXCITED MACHINE.

In the equations hitherto considered it was assumed the armature rotated in a magnetic field, the quantity of w was specified by the symbol N. Nothing was specified a the kind of field-magnets; and the general formula dedu is of course applicable for all kinds, provided their magn power is known. In magneto-dynamos in which the fiel due to permanent magnets of steel, N depends both on magnetism of the steel and on the iron core of the armat The number of lines that find their way through the arma is, however, lessened by the reaction of the armature whe large current is being drawn from the machine. If the m netism of the field-magnets were so overpoweringly grea compared with that due to the armature coils, that this reaction were insignificantly small, then, since our fundamental formula is:—

$$E = n C N,$$

E would, for any given magneto machine, be directly proportional to n, the speed of rotation. But we know in practice that this is not the case. Suppose we turn a magneto machine at 600 revolutions per minute (n = 10, for then there will be 10 revolutions per second) and get, say, 17 volts of electromotive-force from it, then, if there were no reactions from the armature, turning it at 1200 revolutions per minute ought to give exactly 34 volts. This is never quite attained; though in many machines, as, for example, in the laboratory-pattern magneto-Gramme machines made by Breguet (Fig. 7, p. 15), the direct proportion is very nearly attained even with much higher speeds.

Relation between Speed and Electromotive-force. Dead-Turns.

If the current in the armature is kept constant by increasing the resistances of the circuit in proportion to the speed, the demagnetizing action of the armature can be kept constant, even though the machine is giving out a current. In some experiments made by M. Joubert at different speeds, the electromotive-force was measured by an electrometer which allowed no current whatever to pass. The only possible reactions were those due to possible eddy-currents in the core: and the theoretical law was almost exactly fulfilled. The observations are given below, and plotted in Fig. 146, in which the straightness of the "curve" shows how nearly truly the theoretical condition was attained.[1]

Speed	500	720	1070	revolutions per minute.
Electromotive-force ..	103	145	208	volts.

The departure from a straight line observed with high speeds is probably due to the demagnetizing effect of eddy-currents in the rotating masses.

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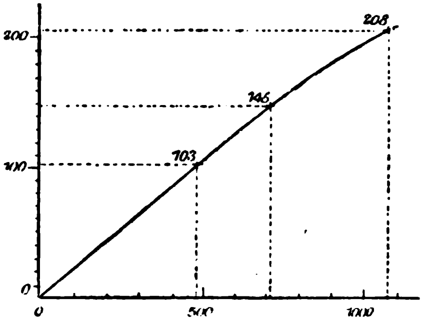
[1] See also experiments by Mordey, *Journal I.E.E.*, xix. 233, 1890.

The number of turns by which the speed, at any ou exceeds the number that would be needed for strict pr tion is called the *dead-turns*.

FIG. 146.



CURVE SHOWING RELATION BETWEEN SPEED AND ELECTROMOTIVE-F

Potential at Terminals of a Dynamo. Lost Volts.

The potential at terminals of the magneto machine— indeed of every dynamo—is, when the machine is doing work, less than E, the total induced electromotive-f because part of E is employed in driving the current thr the resistance of the armature. The symbol e may conveniently used for the difference of potential bet terminals. Only when the external circuit is open, so th current whatever is generated, e = E. It is convenie have an expression for e in terms of the other quant seeing that when any current is being generated it is possible to measure E directly by a voltmeter or b electrometer, whereas e can always be so measured.

Let r_a be the internal resistance of the machine, that say the resistance of the armature coils, and of every else in circuit between the terminals; and let R be resistance of the external circuit. Then, by Ohm's law be the current,

$$E = i(r_a + R).$$

But by Ohm's law also, if e be the difference of potential between the terminals of the part of the circuit whose resistance is R,

$$e = i\,\mathrm{R};$$

whence

$$\frac{e}{\mathrm{E}} = \frac{\mathrm{R}}{r_a + \mathrm{R}}; \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad [\mathrm{III.}]$$

also

$$e = \frac{\mathrm{R}}{r_a + \mathrm{R}}\,\mathrm{E}.$$

It is also convenient to note that

$$\mathrm{E} = \frac{r_a + \mathrm{R}}{\mathrm{R}}\,e;$$

for this formula enables us to calculate the value of E from observations of e made with a voltmeter. But often the values of R are unknown: hence the following is more useful. By subtracting the second of the above equations from the first of them we get :—

$$\mathrm{E} - e = i\,r_a$$

or

$$e = \mathrm{E} - i\,r_a \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad [\mathrm{IV.}]$$

This is equivalent to saying that the volts at the terminals are equal to the whole volts generated in the armature less the volts needed to drive the current i through the internal resistance r. The volts $i\,r_a$ which are thus not available in the external circuit, are called the *lost volts*: they will be less the smaller the internal resistance is. If e is observed by applying a voltmeter, then E can be found by adding to it the lost volts; and these can be calculated by measuring with an amperemeter the current flowing through the armature and multiplying this by the known internal resistance.

Relation between whole Electromotive-force and Differe Potentials at the Terminals.

The essential distinction pointed out above betwee
whole electromotive-force E, and that part of it whi
available as a difference of potentials at the terminals *e*,
be further illustrated by the following geometrical de
stration, which is due to Herr Ernst Richter.[1]

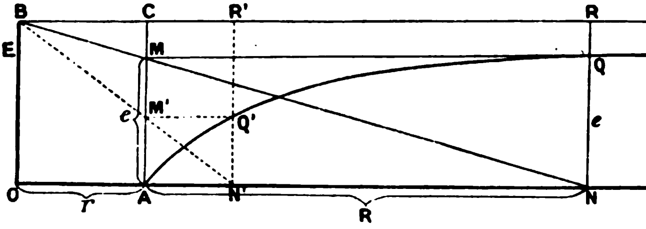
In a machine (such as are chiefly dealt with later) in
e is constant, E will not be constant, except in the unattai
case of a machine which has no internal resistance.
represent the internal resistance of the machine, incl
that of the armature and of any magnet-coils that a
the main circuit ($r = r_a + r_m$) ; then,

$$E = e + i r.$$

If E is constant, then *e* cannot be constant when *i* v
and if *e* is constant, E cannot be. We have then two cas
consider :—

(1) E *constant.*—Take resistances as abscissæ and ele
motive-forces as ordinates, and plot out (Fig. 147) O A

FIG. 147.



A N = R, O B = E. The line B N represents the f
potential through the entire circuit. Of the whole el
motive-force O B, a part equal to C M is expende
driving the current through the resistances *r*, leaving the
A M available as the difference of potential at the term

---

[1] *Elektrotechnische Zeitschrift*, iv. 161, April 1883.

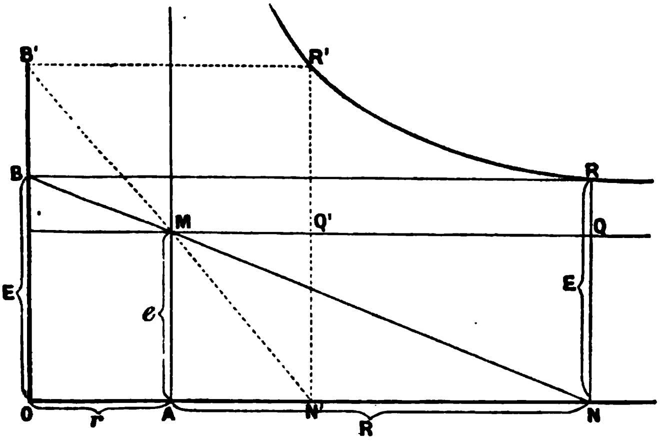
when the total resistance of the circuit is represented by the length from O to N. Accordingly, at N erect a vertical line N Q equal to A M. Take a less external resistance R′ = A N′ and by a similar process we find that the corresponding value of *e* is A M′ or N′ Q′. Similarly, any number of points may be determined; they will all lie on the curve A Q Q′, which therefore shows how, as the external resistance is increased the terminal potential rises, whilst the whole electromotive-force remains constant and is represented by the horizontal line B R. The equation of this curve is given by the condition

$$\frac{E - e}{E} = \frac{r}{R + r}, \checkmark$$

whence $(E - e)(R + r) = Er =$ constant; which equation is the equation of an equilateral hyperbola having O B and B R as asymptotes.

(2) *e constant.*—As in the preceding case, O A = r; A N = R; and A M = e. From N (Fig. 148) draw the line

FIG. 148.



N M and produce it backwards to B. Then O B represents that value of E which will give *e* volts at terminals when R = N M. Accordingly set off at N the line N R = O B.

In a precisely similar way draw N′ B′, to correspond with other value of R, and make N′ R′ equal to O B′. N′ R′ r sents the value of E when the value of the external resist R is equal to A N′. By determining other values we o the successive points of the curve R R′, which shows hov whole electromotive-force must vary in order to mainta constant difference of potentials at the terminals, as r sented by the horizontal line M Q. The equation to this curve is given by the condition

$$\frac{E - e}{r} = \frac{e}{R}$$

or $$(E - e)\,R = e\,r = \text{constant.}$$

This curve is also an equilateral hyperbola.

The Separately-excited Dynamo.

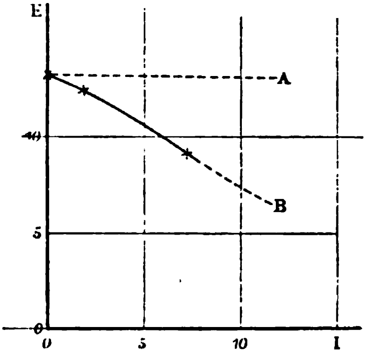
For separately-excited dynamos the same formulæ good as for magneto-dynamos; but in this case N dep upon the strength of the independent exciting current.

In estimating the nett (or commercial) efficiency separately-excited dynamo, the energy spent per secon exciting the field-magnets ought to be taken into account

Characteristic of Magneto Machine, and of Separately-ex Dynamo.

In the magneto-dynamo the magnetism of the magnets is approximately constant. This has given rise common idea that in such machines the electromotive- depends on the speed alone. This is not true. For owin the cross-magnetizing and demagnetizing tendency of currents in the armature coils, the number of magnetic that actually traverses the armature core diminishes whe currents in the armature are strong. The stronger the cu in the armature the stronger the reaction. As will be expla (p. 245), it is convenient to plot out certain curves, know *characteristics*, to exhibit the relation that subsists between the electromotive-force and the current under different conditions of speed, resistance, &c. Usually one of the conditions assumed is that the speed is constant. Such curves are particularly useful for studying the various reactions that exist between the field-magnet and armature. Fig. 149 gives the characteristic of a small magneto machine of the laboratory type, having a Gramme ring. It was capable of lighting two small Swan lamps of about 5 candle-power. On open circuit the electromotive-force was 13·1 volts at a speed of 1400 revolutions per minute. The value of E, the total electromotive-force generated in the armature, fell from 13·1 to 12·4 volts when a current of 1·8 amperes was taken from the machine; and when it was short-circuited to give 6·1 amperes the value of E fell to 9·2 volts. This was, however, an exceptionally bad case.

FIG. 149.



CHARACTERISTIC OF MAGNETO MACHINE.

The reaction of the armature current was here very strongly marked. Were there no reaction, the characteristic would follow the dotted line to A instead of dropping down to B. As explained on p. 89, the demagnetizing tendency of the armature current increases with the lead given to the brushes.

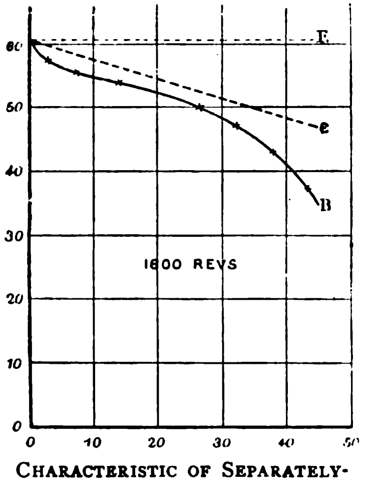
The characteristics of separately-excited dynamos exhibit a similar decline in the electromotive-force; and the reasons are exactly similar. A careful study of these machines was made in 1884 by Mr. W. B. Esson,[1] who gives the following curve for a separately-excited dynamo having a modified

---

[1] *Electrical Review*, xiv. 393, April 1884. See also papers by M. Marcel Deprez, *Comptes Rendus*, xciv. pp. 15 and 86, 1882.

Pacinotti ring armature. The line E (Fig. 150) repres the total electromotive-force if there were no reactions. line ε represents the values of the potential between

FIG. 150.



CHARACTERISTIC OF SEPARATELY-EXCITED DYNAMO.

brushes of the machine (ca ε in this book in contra tinction to E the whole e tromotive-force) as it wo be if there were no react

The curved line B gives actually-observed values when different currents v taken from the mach The great drop at the lo end of the curve is proba due to the greater dem netizing effect of the ar ture current when ther (as with strong currents considerable lead at brushes. The character always shows such downw curvature more when the field-magnets are weakly exci (See Fig. 420.)

Efficiency and Economic Coefficient of Dynamos.

Suppose that we know the actual mechanical horse-pc applied in driving a dynamo. This can be measured dire either by using a transmission dynamometer, or by tal an indicator diagram from the steam-engine that is dri it, or, in certain special cases where the field-magnets ca pivoted or counterpoised, by applying the method origin pursued by the Rev. F. J. Smith, and later described M. Marcel Deprez and by Professor Brackett, in which actual mechanical interaction between the armature and f magnets is utilized to measure the horse-power used in dri the machine. If, then, we know the horse-power applied, if we measure the "activity" of the dynamo, that is to sa output of electrical horse-power, we have by comparing the mechanical power absorbed with the electrical activity developed, a measure of the "efficiency" of the dynamo as an economical converter of mechanical energy into electrical energy. It must, of course, be borne in mind that part of the electrical energy developed is inevitably wasted in the machine itself, in consequence of the unavoidable resistance in the wire of the armature, and, in the case of self-excited dynamos, in the wire of the field-magnet coils. There must therefore be drawn the distinction mentioned on p. 117 between the gross efficiency of the machine, or as it is sometimes called, its "efficiency of electric conversion," and its nett efficiency or commercial efficiency.

To express efficiency, whether gross or nett, we must, however, have the means of measuring the electric output of the dynamo, or of any part of its circuit.

As is well known, the energy per second of a current can be expressed, provided two things are known, namely, the number of amperes of current, and the number of volts of potential between the two ends of that part of circuit in which the energy to be measured is being expended. The number of amperes of current is measured by a suitable amperemeter; the number of volts of potential by a suitable voltmeter. The product of the volts into the amperes expresses the electric energy expended per second in terms of the unit of activity denominated the "watt" (see Appendix A, on Units). As 1 horse-power is equal to 746 watts, the number of volt-amperes (*i. e.* of watts) must be divided by 746 to give the result in horse-power. If i represents the current in amperes, and e the difference of potential in volts, then the "activity" or "electric power," for which we may use the symbol w, may be written

$$w = \frac{e\,i}{746}. \quad . \quad . \quad . \quad . \quad . \quad . \qquad [\text{V.}]$$

The ratio of the useful electrical energy realized in the external circuit to the total electric energy that is developed in the armature is called the "electrical efficiency" or “economic coefficient” of the machine. It may be expres algebraically as follows:—If through an armature ther flowing a current of i_a amperes, and its total electromot force be E volts, then its total electric activity will be

$$= E\, i_a \text{ (watts).}$$

If the volts of pressure between the terminals of the dyna be e, then the useful activity is

$$= e\, i \text{ watts.}$$

Using the symbol η for the “economic coefficient,’ so-called “electrical efficiency,” we have

$$\eta = \frac{\text{useful activity}}{\text{total activity}} = \frac{e\, i}{E\, i_a},$$

or, if the machine has no shunt, so that i and i_a are the sa thing,

$$\eta = \frac{e}{E}.$$

But we know that the ratio $\frac{e}{E}$ depends on the relation of internal and external resistances, for

$$\frac{e}{E} = \frac{R}{r + R} \text{ (see equation [III.]),}$$

where R is the resistance of the external circuit, and r internal resistance (armature, magnets, &c.) of the mach Hence, for a series dynamo or a magneto machine,

$$\eta = \frac{R}{r + R}\cdot \qquad . \quad . \quad . \quad . \quad . \quad . \quad . [$$

Obviously, this coefficient will approach more and n nearly to *unity* the more that the value of r can be diminis For if a machine could be constructed of *no* internal resista there would be none of the energy of the current expen in driving the current through the armature and wastec heating its coils.

We shall see later on how the expression for the econo coefficient η must be modified in the case of shunt dynamos and compound dynamos.

Returning now to the real efficiency of the machine, let us use the symbol W for the mechanical work-per-second, or horse-power, actually used in driving the armature. And, remembering that the gross electric activity of the machine is $\frac{E i_a}{746}$, we have for the *gross efficiency*, or efficiency of electric conversion,

$$\frac{E\, i_a}{W \times 746},$$

and for the *nett efficiency*, or useful commercial efficiency,

$$\frac{e\, i}{W \times 746}.$$

It will be seen that, as the first of these expressions contains E, and the second e, the nett efficiency can be obtained from the gross efficiency by multiplying by η, the economic coefficient.

It must be noticed before passing from this topic that since i, the strength of the current, enters into each of the expressions for efficiency as a factor, and as i depends not only on the resistance of the machine itself, but on that of the lamps, or other parts of the system which it is used to feed, it is somewhat misleading to talk of the efficiency of the *dynamo*, as if the efficiency was a property of the dynamo. On the contrary, not only the gross efficiency, but also economic coefficient, and therefore *a fortiori*, the nett efficiency, depend on the external resistance, that is to say on the number of lamps that may happen to be alight! But still there is a sense in which these expressions are justifiable. Every dynamo is designed to furnish a certain quantity of lamps, and therefore to carry a certain average current. Its efficiency and coefficient of economy ought therefore to be expressed in terms of that current (and of that external resistance) which may be considered the fair working load of the machine.

Variation of Economic Coefficient with Current.

It will be noticed that in the case of the series mach considered above, the value of η will be different when R external resistance is varied. When R is very great co pared with r, then the value of η is very nearly $= 1$; but small values of R, the value of η diminishes indefinitely. when R is large the current is small, and when R is small current is large. It appears, therefore, that a series dyna has its maximum value for the economic coefficient when i doing its minimum of work.

THE SERIES DYNAMO.

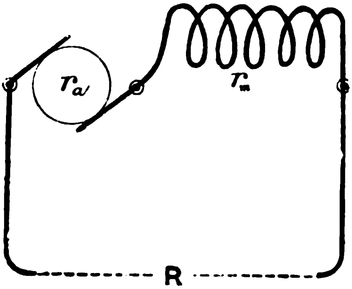
In the series dynamo (see Fig. 151, also Fig. 39), there but one circuit, and therefore but one current, whose stren i depends on the elect motive-force E and on sum of resistances in the cuit. These are :—

R = the external (variab resistance.

r_a = the resistance of armature.

r_m = the resistance of field-magnet coils

FIG. 151.



By Ohm's law—

$$E = (R + r_a + r_m)\, i.$$

Also e, the difference of potential between the terminals the machine, is

$$e = R\, i.$$

It is also convenient to find an expression for the differe of potential between the brushes of the machine ; the vo measured here being greater than e, because of the resista of the field-magnets ; and less than E, because of the resi ance of the armature coils. For this difference of potent between brushes we will use the symbol ϵ. Then, by Ohm's law, remembering that the current running through r_m and R is of strength i, we have

$$\epsilon = (R + r_m)\, i\,;$$

whence, also,

$$e = E - (r_a + r_m)\, i.$$

Economic Coefficient of Series Dynamo.

From Joule's law of energy of current it follows that the economic coefficient η, which is the ratio of the useful electric energy available in the external circuit to the total electric energy developed, will be

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{i^2 R t}{i^2 (R + r_a + r_m) t} = \frac{e}{E},$$

or

$$\eta = \frac{R}{R + r_a + r_m}. \quad . \quad . \quad . \quad . \quad \text{[VII]}.$$

This is obviously a maximum when r_a and r_m are *both* very small. Sir W. Thomson recommends that r_m be made a little smaller than r_a.

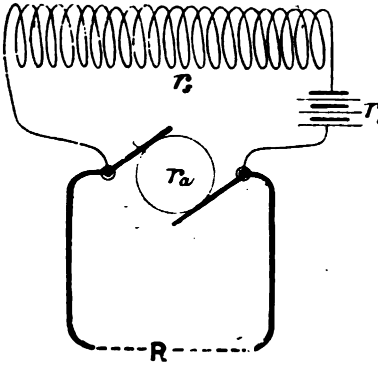
Example:—In a Phœnix arc-lighting dynamo, designed by Esson, $r_a = 3{\cdot}448$ ohms, and $r_m = 4{\cdot}541$ ohms. If $i = 10$ amperes, the lost volts will be 79·89.

Further than this we cannot go without introducing some kind of an expression to connect E with the number of ampere-turns in the exciting coils. If we introduce the convenient approximate formula of Frölich, as given on p. 167, we shall obtain some approximate dynamo formulæ. These were given in detail on pp. 401 to 410 of the third edition of this book; wherein also, at pp. 620, 627, and 632, were given the more elaborate developments by Frölich, by Clausius, and by Rücker.

THE SHUNT DYNAMO.

In the shunt dynamo, there are two circuits to be c
sidered ; the main circuit, and the shunt circuit. The syml
used have the following meanings.

FIG. 152.



R = resistance of external main circuit (leads, lamps, &
r_a = resistance of armature.
r_s = resistance of the shunt circuit (magnet coils).
i = the current in the external main circuit.
i_a = the current in the armature.
i_s = the current in the shunt circuit (the lost amperes

Then, clearly,

$$i_a = i + i_s$$

because the current generated in the armature splits i
these two parts in the main and shunt circuits, and is equa
their sum.

We may call that part of the whole current which retu
through the shunt, and is not available in the external circ
the *lost amperes :* in a good modern machine they are at n
only 2 or 3 per cent. of the whole output of current. If
the volts at the terminals, the lost amperes may be calcula
as

$$i_s = e \div r_s$$

For example, in the Kapp dynamo (p. 488), giving 200 *amperes* at a pressure of 105 *volts* at terminals, r_s was 31 ohms, hence the *lost amperes* were 3·4, and total current in armature at full load 203·4 *amperes.*

Also, by Ohm's law, we have for e the electromotive-force between terminals,

$$e = R\,i,$$

and also

$$e = r_s\,i_s\,;$$

because the terminals for the main circuit are also the terminals for the shunt circuit.

Further, since the nett resistance of a branched circuit is the reciprocal of the sum of the reciprocals of the resistances of its parts, the nett external resistance from terminal to terminal is equal to $\dfrac{R\,r_s}{R + r_s}$; and hence it follows that

$$E = \left(r_a + \frac{R\,r_s}{R + r_s}\right) i_a.$$

We may at the same time find an expression for that part of the whole electromotive-force which is being employed solely to overcome the resistance of the armature, and which is, of course, the difference between E the total electromotive-force, and e the effective electromotive-force between terminals.

Ohm's law at once gives us

$$E - e = r_a\,i_a,$$

or

$$E - e = r_a\,(i + i_s).$$

From this we also get

$$e = E - r_a\,(i + i_s). \quad . \quad . \quad . \quad . \quad [\text{VIII.}]$$

We will also find an expression for E in terms of e, and the various resistances. Taking as above

$$E = \left(\frac{R\,r_s}{R + r_s} + r_a\right) i_a,$$

and writing for i_a its value as $i + i_s$, and for these $\frac{e}{R}$ $\frac{e}{r_s}$ respectively, we get

$$E = e\left\{\frac{R r_s + R r_a + r_a r_s}{R + r} \times \frac{R + r_s}{R r_s}\right\},$$

or

$$E = e \times r_a\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right). \quad . \quad . \quad [\text{VIII.}$$

It may be noted that the expression $\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right)$ is sum of three conductivities of three paths, and is there equal to the conductivity of these three paths united in par with one another ; that is to say, the conductivity as meas from brush to brush with the external circuit and shunt ci joined up. Or, if we write $\mathfrak{R}$ for the resistance of the w system of machine and circuit, as thus measured from b to brush, then the equation may be written

$$E = e \times \frac{r_a}{\mathfrak{R}}.$$

Economic Coefficient of Shunt Dynamo.

The economic coefficient η, is the ratio of the useful electric e available in the external circuit to the total electric energy devel

By Joule's law there is developed in t seconds in the ext circuit

$$\text{useful work} = i^2 R t,$$

and in the same time there is wasted on heating,

$$\text{energy spent in shunt} = i_s^2 r_s t,$$

and

$$\text{energy wasted in armature} = i_a^2 r_a t;$$

whence

$$\frac{\text{useful work}}{\text{total work}} = \frac{i^2 R}{i^2 R + i_s^2 r_s + i_a^2 r_a}$$

$$= \frac{1}{1 + \frac{R}{r_s} + \frac{i^2 r_a + 2 i i_s r_a + i_s^2 r_a}{i^2 R}}$$

$$= \frac{1}{1 + \frac{R}{r_s} + \frac{r_a}{R} + 2\frac{i_s r_a}{i R} + \frac{r_a}{R}\left(\frac{i_s}{i}\right)^2}$$

$$= \frac{1}{1 + \frac{R}{r_s} + \frac{r_a}{R} + 2\frac{R}{r_s}\cdot\frac{r_a}{R} + \frac{r_a}{R}\left(\frac{R}{r_s}\right)^2}$$

$$= \frac{1}{1 + \frac{R}{r_s} + \frac{r_a}{R} + 2\frac{r_a}{r_s} + R\frac{r_a}{r_s^2}}$$

$$= \frac{1}{1 + \frac{R}{r_s}\left(1 + \frac{r_a}{r_s}\right) + \frac{r_a}{R} + 2\frac{r_a}{r_s}}.$$

Now, for brevity, write for the total internal resistance, $r_a + r_s$, the **single symbol** r—

$$\eta = \frac{1}{1 + \frac{R r}{r_s\, r_s} + \frac{r_a}{R} + 2\frac{r_a}{r_s}}.$$

For this ratio to be a maximum it is clear that,

$$\frac{d\left(1 + \frac{R}{r_s}\cdot\frac{r}{r_s} + \frac{r_a}{R} + 2\frac{r_a}{r_s}\right)}{dR} \text{ must } = 0,$$

or

$$\frac{r}{r_s^2} - \frac{r_a}{R^2} = 0;$$

whence

$$R^2 = \frac{r_a r_s^2}{r} = r_a r_s \frac{r_s}{r},$$

and

$$R = \sqrt{r_a r_s}\sqrt{\frac{r_s}{r}}, \quad . \quad . \quad . \quad . \quad . \quad . \qquad [IX.]$$

or

$$R = r_s\sqrt{\frac{r_a}{r}} \quad . \quad . \quad . \quad . \quad . \quad . \qquad [IXa.]$$

This equation determines what particular resistance of the ex
main circuit will give the best economy with given internal resist
Now substitute this value in those terms of the equation for η
contain R, and we get as their values :—

$$\frac{Rr}{r_s^2} = \frac{r}{r_s}\sqrt{\frac{r_a}{r}} = \frac{\sqrt{r_a r}}{r_s},$$

$$\frac{r_a}{R} = \frac{r_a}{r_s}\sqrt{\frac{r}{r_a}} = \frac{\sqrt{r_a r}}{r_s};$$

whence

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{1}{1 + 2\,\frac{\sqrt{r_a r}}{r_s} + 2\,\frac{r_a}{r_s}}$$

This may be still further simplified, for we know that the
ance of the shunt is very high compared with that of the arm
possibly from 300 to 1000 times as great. If, then, $\frac{r_a}{r_s}$ is so
a term in comparison with the other term as to be negligible,

$$\eta = \frac{1}{1 + 2\,\frac{\sqrt{r_a r}}{r_s}}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad .$$

and since r_a is small compared with r_s, r is very nearly eq
r_s, so that we may write, as an approximate equality,

$$\eta \doteqdot \frac{1}{1 + 2\,\frac{\sqrt{r_a r_s}}{r_s}};$$

or

$$\eta \doteqdot \frac{1}{1 + 2\sqrt{\frac{r_a}{r_s}}} \quad . \quad . \quad . \quad . \quad .$$

This latter approximate value is identical with that given
W. Thomson in the Report of the British Association for
the equation No. [X.] is, however, more correct.

It may be pointed out that it follows from equ
No. [IX.] above, that when the resistance of the armat

small compared with that of the shunt, so that r_s may be taken as equal to the value of r (which would be highly desirable if it could be attained in practice), then we should have

$$R = \sqrt{r_a . r_s}\,; \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{XII.}]$$

that is to say, when the proportion between r_a and r_s is made as favourable as possible, then the best external resistance to work with from the economic point of view is that resistance which is a geometric mean between the resistances of the armature and of the shunt coils, and any departure from this will diminish the value of the economic coefficient.

Practical Rules for Economic Design.

This affords us some practical imformation how to apportion the resistances in a shunt dynamo. Let the question be thus stated. Given the resistance of the armature r_a, what must the shunt resistance be so that the dynamo may (under favourable proportions of external resistance R) have an economic coefficient of 90 per cent. From equation [XI.] we get

$$\frac{90}{100} = \frac{1}{1 + 2\sqrt{\frac{r_a}{r_s}}}$$

$$\frac{100}{90} = 1 + 2\sqrt{\frac{r_a}{r_s}},$$

$$10 = 180\sqrt{\frac{r_a}{r_s}},$$

$$r_s = (18)^2\, r_a,$$

$$r_s = 324\, r_a.$$

No shunt machine can give in the external circuit as much as 90 *per cent. of its total electric energy unless its shunt has a resistance at least* 324 *times as great as that of its armature.*

A good practical rule would be the following:—A
tain what number of lamps will be the usual full load: r
the resistance of them when connected to the mains.
the armature resistance be one-twentieth of this; and l
shunt resistance be twenty times as great as this. I
case about 4 per cent. will be wasted in the armatur
about 4 per cent. in the shunt, leaving a margin of a
over 90 per cent. for the economic coefficient.

In a shunt machine described by Sir C. W. Siemens
Philosophical Transactions, 1880, the results were:—

——	Armature.	Shunt Magnet.	r_s/r_a.	η observed per cent.
Siemens	0·204	11·26	48·4	69·0

In an Edison machine ("K," 250 lights) tested at M
the values were:—

——	Armature.	Shunt Magnet.	r_s/r_a.	η observed.
Edison, "K"	0·0361	13·82	382·8	88·6

The Edison-Hopkinson machine, described on p. 520, gav

Resistance when cold	0·009947	16·93	1702	93·6

The Kapp dynamo alluded to above, p. 230, and depic
Plates I. & II., gave, including the series coil with the armatu

(Cold)	0·0306	29·133	952	92
(Warm)	0·0329	31·08	945	

CHAPTER X.

CHARACTERISTIC CURVES.

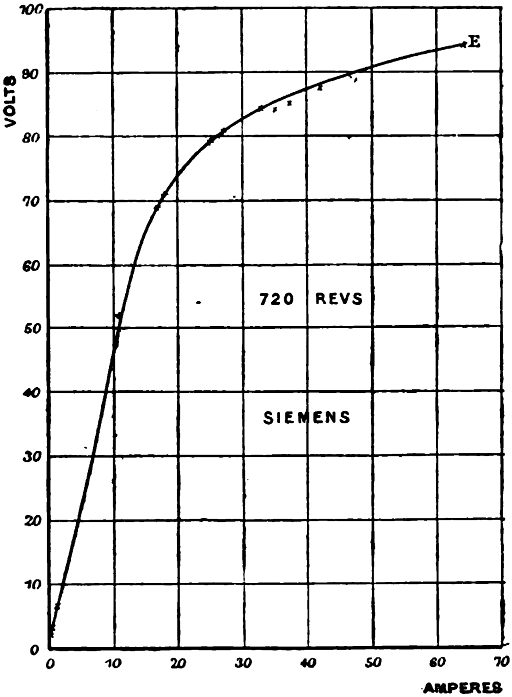
So many practical problems in the construction of dynamo-electric machines are in the present state of science solved by the use of graphic diagrams, and particularly by the use of certain curves technically called *characteristics*, that the method of constructing and using them forms an important part of the theory of the dynamo. For many practical purposes no other method is half so useful.

The characteristic curve stands indeed to the dynamo in a relation very similar to that in which the indicator diagram stands to the steam-engine. As the mechanical engineer, by looking at the indicator diagram of a steam-engine, can at once form an idea of the qualities of the engine, so the electrical engineer, by looking at the characteristic of the dynamo can judge of the qualities and performance of the dynamo. The comparison may even be said to reach farther than this.

The steam-engine indicator diagram serves two purposes which, though not unconnected with one another, are yet distinct. When the scale on which the diagram is drawn is known, it gives direct information as to the horse-power at which the engine is working, depending on the total area enclosed by the curve, and quite irrespective of its form. But even though the actual scale be not known, the details of the form of the curve at its various points give very definite information to the engineer as to the working of the engine, the perfection of the exhaust, the setting of the valves, the efficiency of the cut-off, and the adequacy of the supply pipes and port-holes of the valves.

So also the characteristic curve of the dynamo may serve two functions. When the scale on which it is drawn is known it tells the horse-power at which the dynamo works ; r can indicate at what horse-power the dynamo may be worl to the greatest profit. But even though the actual scale not known, the details of the form of the curve afford defi information as to the conditions of the working of the machi the degree of saturation of its magnets, the sufficiency of field-magnets in proportion to the armature, and the goodı of the design in several respects.

FIG. 153.



CHARACTERISTIC CURVE OF A SERIES DYNAMO.

The suggestion to represent the properties of a dyna machine by means of a characteristic curve is due to Hopkinson, who in 1879 described such curves to the Inst tion of Mechanical Engineers, and gave the curve of Siemens dynamo reproduced in Fig. 153. The name "characteristic" was assigned in 1881 by M. Marcel Deprez[1] to Hopkinson's curves; and the excellence of the name has been attested by its general adoption.

Dr. Hopkinson's object was to represent the relation subsisting between the electromotive-force and the current; he therefore constructed from observations a curve in which the abscissæ measured horizontally represent the number of amperes of current flowing, and the vertical ordinates the corresponding values of the electromotive-force. The following table (taken with some trifling modifications from Dr. Hopkinson's paper in the *Proceedings of the Institution of Mechanical Engineers*, 1879, p. 249) gives the observed values of i the strength of the current, and E the electromotive-force, of a certain series-wound dynamo.

EXPERIMENTS ON SIEMENS DYNAMO AT SPEED OF 720 REVOLUTIONS PER MINUTE.

Current (in amperes). i	Resistance (in ohms). R	Electromotive Force (in volts). E
0·0027	1025	2·72
0·48	8·3	3·95
1·45	5·33	7·73
16·8	4·07	68·4
18·2	3·88	70·6
24·8	3·205	79·5
26·8	3·025	81·1
32·2	2·62	84·4
34·5	2·43	83·8
37·1	2·28	84·6
42·0	2·08	87·4

It may be remarked that the electromotive-force E is the total electromotive-force generated in the machine, and must not be confounded with e the difference of potential between the terminals as measured by a voltmeter, or other sim instrument. In many cases we now prefer to plot *e* inst of E; but that was not Hopkinson's original method. determined E by measuring *i* and multiplying it by the t resistance of the circuit; for by Ohm's law *i* R = E. should also be remarked that the dynamo was a "se dynamo," shunt-wound machines not having at that come into vogue.

---

[1] Vide *La Lumière Électrique*, Dec. 3, 1881; where, however, Deprez gives a method of observation that is open to the objection that it neglects the armature reactions.

Before entering into other points, it may be worth w to consider the meaning of the curve. It begins at a poi little above the origin. This shows that there was a sr amount of residual magnetism remaining permanently in field-magnets. The curve ascends at first at a steep angle, t curves round and eventually assumes a nearly straight cou but at a gentler slope than before. Whence arise these typ forms? It is known that the electromotive-force of a dyna depends not only on the speed of running and on the numbe coils of wire in the armature, but also on the intensity of magnetic field. Now if the speed is constant—it was ma tained at 720 revolutions per minute in Hopkinson's exp ments—the only variable of importance is the intensity of magnetic field. As the magnetism of the field-magnets r and grows toward its maximum, the intensity of the field rises and grows toward a maximum, and so does the indu electromotive-force. We might therefore expect, as Hopkin points out, that the curve which represents the relation betw the current and the electromotive-force of the series-wo dynamo should exhibit peculiarities of form similar to th of the curve which represents the relation between magnetizing current and the magnetization of an elec magnet; and a comparison of Fig. 153, the "characterist of the dynamo, with Fig. 92, the "magnetization curve" o electromagnet, will suffice to reveal the analogy. It m however, be pointed out that the intensity of the field d not depend only on the strength of the field-magnet, bu affected by the current that is circulating in the arma coils in consequence of the reaction between the fi magnets and armature. Moreover, certain prejudicial eff arising from self-induction in the armature coils come into play with high speeds and strong currents, and prevent the electromotive-force from being proportional to the strength of the field. Hopkinson's statement that the characteristic of the dynamo may also be taken to represent the magnetization of the field-magnet, cannot therefore be accepted except with the reservation that it is true only when these reactions are negligibly small, which is seldom the case.

It is possible for a dynamo to be made to draw its own characteristic by mechanically moving the pencil relatively to the paper (as in steam indicators) by means of two electromagnets, one of them being excited by the main current, the other being connected as a shunt to the terminals of the machine.

Dr. Hopkinson, in the paper alluded to, and in a second one published in the *Proc. Inst. Mech. Engin.*, in April 1880, p. 206, pointed out a great many of the useful deductions to be drawn from a consideration of these curves. Some other deductions have been made by M. Marcel Deprez, for which the reader is referred to *La Lumière Électrique*, of Jan. 5th, 1884. Dr. Frölich has also published several important papers on the subject in the *Elektrotechnische Zeitschrift* for 1881 and 1885. Dr. Hopkinson has returned to the subject in a lecture before the Institution of Civil Engineers, "On Some Points in Electric Lighting," April 1882.

Horse-power Characteristics.

As mentioned at the beginning of this chapter, if the characteristic curves are drawn to scale the activity of the dynamo may be read off from them in horse-power. The product of the current into the potential is proportional to the rate at which the electric energy is being evolved.[*] The product of one volt of potential into one ampere of current is sometimes called one *volt-ampere*, and has also been called by the special name of one *watt.* One watt or volt-ampere is equal to $\frac{1}{746}$ of a horse-power. To calculate the horse-power (electrical) evolved in the circuit when the dynamo is running at any particular speed, with a particular number of lamps in circuit, two measurements have ordinarily to be made—the volts of electromotive-force and the amperes of curr These must then be multiplied together and divided by to obtain the horse-power. But if the characteristic of dynamo at the particular speed be known, a reference to curve will show at once what the electromotive-force is corresponds to any particular current. For example, in Siemens dynamo examined by Hopkinson, the characteri of which is given in Fig. 153, p, 246, suppose the dynamo working through such a resistance as to give 30 amp when running at 720 revolutions, we see at once that corresponding electromotive-force is 83. Hence

$$\frac{83 \times 30}{746} = 3 \cdot 3 \text{ horse-power.}$$

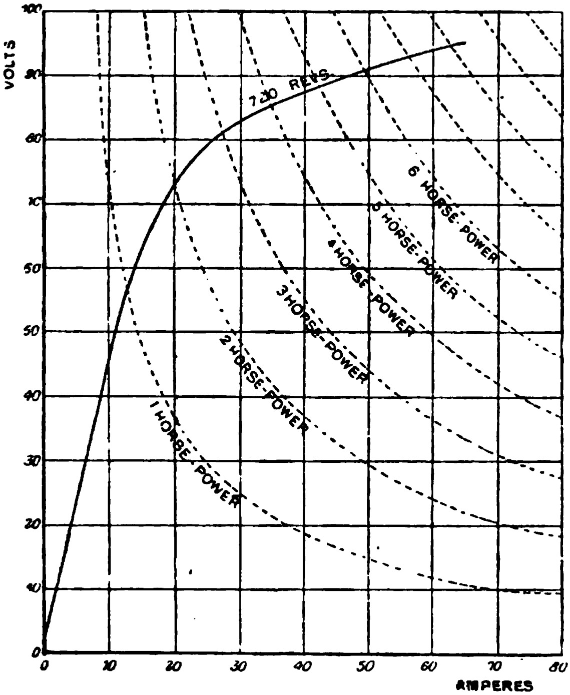
Now to obviate such calculations we may plot out on diagram some additional curves crossing the characteris and mapping them out into equal values of horse-po These "horse-power lines" are nothing else than a set of r angular hyperbolas. For example, the 1-horse-power will pass through all the points for which the product of v and amperes is equal to 746. It will therefore pass thro the point corresponding to 74·6 volts and 10 ampe through 37·3 volts and 20 amperes; through 14·92 volts 50 amperes, &c., because the products in each of those c is equal to 746 watts or 1 horse-power. The 2-horse-po line will pass through points whose product values are ec to 746 × 2, and the other lines in the same way. Fig. shows the characteristic of the Siemens machine, reprodu from Fig. 153 above, but with the horse-power lines added

In this case the volts plotted are the total elec motive-force "E," of the dynamo, and therefore the ho power represents the total electric energy converted second in the circuit of the dynamo. If instead of E we plotted the values of "*e*," the difference of potentials tween the terminals, we should have had a slightly diffe curve, representing the amount of electric energy appea per second in the external circuit and available for us purposes.

A horse-power characteristic of a shunt-wound dynamo is given further on, in Fig. 162.

If the vertical and horizontal scales are not chosen equal, the horse-power lines, though hyperbolæ, are of course distorted.

FIG. 154.

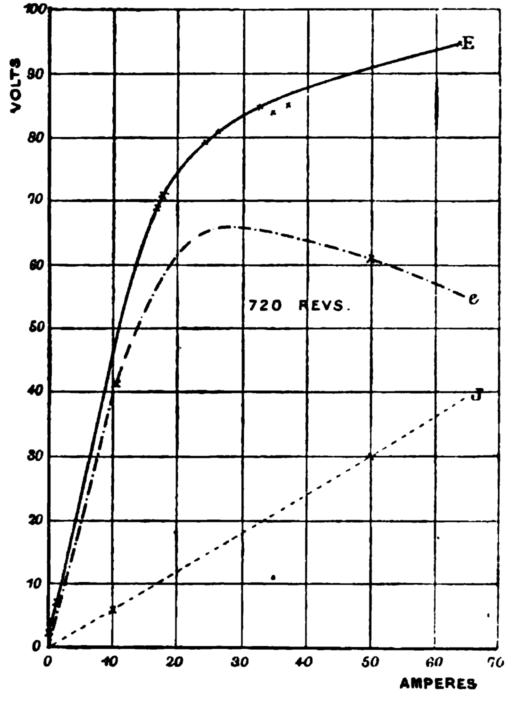


CHARACTERISTIC WITH HORSE-POWER LINES.

"*External*" *Characteristics or Terminal Potential Curves.*

For many purposes it is more useful to know the relation between the current and the "external" difference of potential at the terminals than to know the relation between the current and the whole electromotive-force induced in the armature; and it is mostly easier to measure e than to measure E, seeing that while the former can be directly measured with a voltmeter, the latter can only be got at indirectly. The name *external characteristic* may be given for the sake of distinc to those curves which exhibit the relation between the po tials and the currents of the external circuit. In the se dynamo it is a simple matter to derive one of these cu from the other, provided the internal resistance of the macl (armature and field magnets) is known. In the Sien dynamo examined by Hopkinson in 1879, and of which F 153 and 154 give the total characteristic, the total inte resistance was 0·6 ohm. The curve is reproduced for a t time in Fig. 155, where it is marked "E." Now to forc current of 10 amperes through a resistance of 0·6 of an o would require a difference of potential of 6 volts betweer terminals. Looking at the curve, we see that the wl electromotive-force, corresponding to 10 amperes, was al 46·5 volts. Of this number, 6 were employed, as mentio in overcoming the internal resistance, leaving 40·5 volts the available potential between terminals. Further, when current was running at 50 amperes, there must have been less than 30 volts *lost* in overcoming the internal resistanc 0·6 ohm; and as the value of E for this current is 9 volts, there remain 60·5 volts for *e*. There are now two w open to us of representing these matters on our diagr They are both shown in Fig. 155. The line J is drawn thro the origin, and through the values of 6 volts for 10 amp and 30 volts for 50 amperes. (The tangent of the slope of line J is equal to 6 ÷ 10 = 0·6. We shall see later that slope represents the internal resistance.) Then if the heig of the ordinates from the base line up to the line E repre total volts induced, and if the heights of the ordinates fr the base line up to the line J represent the corresponding v lost in overcoming internal resistance, it follows that *the ference of potentials at the terminals will be represented by differences of the ordinates between the lines* J *and* E. Thi the first way of representing those differences of potenti The second way is to cut off from the tops of the ordina portions equal to those of the line J. This amounts to s tracting the internal volts, which as shown in the algeb theory are equal to $i\,(r_a + r_m)$, from E, and so obtaining values of *e*. These are plotted out in the curve marked "*e*" in the figure; and as this curve represents the available electromotive-force in the external circuit, it obtains the name of *external characteristic* or terminal potential curve. As a matter of fact it is more usual to reverse the operation. The terminal potential values are easily observed with a voltmeter and the current with an ampere-meter. Then the external curve for *e* and *i* is plotted; and by *adding* to the ordinates the corresponding values of the lost volts, and so obtaining the curve for E and *i*. If there is permanent magnetism in the magnets, the characteristics will not start from the origin, but from a point a little above it.

FIG. 155.

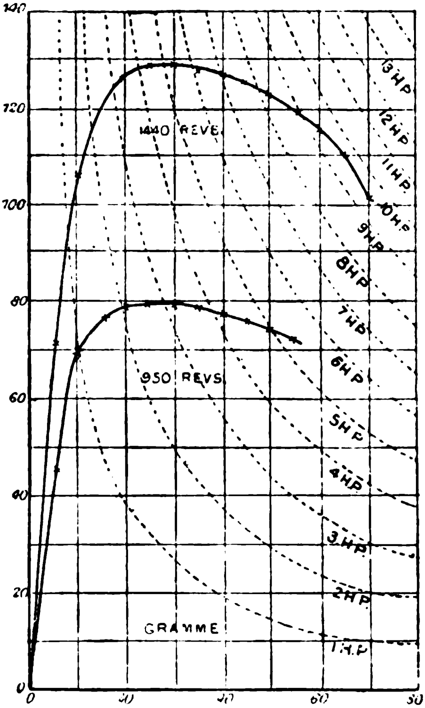


TOTAL AND EXTERNAL CHARACTERISTICS.

Characteristics of Series Dynamo.

The Siemens dynamo of which the characteristic is g in Fig. 153 was a series dynamo. For the sake of compa the characteristic is given in Fig. 156, of an "A" Gra machine also series-wound. This machine had, when it measured by M. Marcel Deprez, 0·41 ohm resistance i

FIG. 156.



CHARACTERISTIC AT DIFFERENT SPEEDS.

armature coils and 0·61 ohm in the coils of the field-mag Two characteristics are given; one corresponding to a s of 1440, the other to a speed of 950 revolutions per mi The horse-power lines are show in dot also. The figure given in the following table.

EXPERIMENTS ON GRAMME SERIES-WOUND DYNAMO.

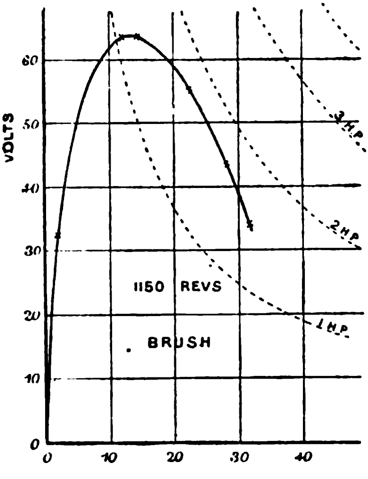
Current (in amperes).	Electromotive Force (in volts).	
	Speed 1440.	Speed 950.
5	72	45
10	107	70
15	122	77
20	127	79
25	129	79
30	128	79
35	128	79
40	127	78
45	125	76
50	123	74
55	120	72
60	116	—
65	110	—
70	101	—

In the series dynamo the magnetization of the magnets increases with the current, and therefore, at first, the electromotive-force increases also, giving the first straight portion of the curve. As the magnets approach saturation the curve turns, and, as the reactions due to the current in the armature now become of relatively great importance, flattens itself and ultimately turns down again.

One circumstance that contributes to the diminution of the electromotive-force when large currents are passing through the armature, is that if the field-magnets are relatively not powerful, the cross-magnetizing effect of the armature current causes a great displacement of the neutral point, and obliges a considerable lead being given to the brushes, with the result that the demagnetizing effect of the armature on the field-magnets (p. 89) becomes greatly increased. The dip in the characteristic is always greater in the case of weak field-magnets. It also occurs most in those machines in which the core of the armature is more nearly saturated than the cores of the field-magnets; for when with large currents the ar ture cores get saturated, the magnetic leakage from the p pieces becomes relatively greater.

One more curve of a series-wound dynamo is give Fig. 157. This is a small Brush machine (intended to su a single arc light) of the old pattern, with solid iron rin which, owing to the peculiar arrangement of the coils p. 458), the reactions of the armature make themselves kn by a very extraordi down-bending of the cha teristic. This is partly to the arrangements cutting out a pair of c as they approach the ne point. It will be not that the maximum ho power of this small mac is 1¾ horse; and that value is only obtained w the reactions have already in. The remarkable dim tion in the electromot force which takes place w the machine is so tre as to demand from it an put which it was never tended to give, is in prac a real advantage. Should the machine be accidentally sh circuited while running, the reactions of the armature vent the production of an injuriously large current, w might overheat the coils. It is considered an advan in machines for arc-lighting, where a nearly constant cu is required, to employ machines with drooping characteris and to work them at this part of the curve.

Fig. 157.



Drooping Characteristic.

Relation of Characteristic to Speed.

We know that the electromotive-force generated i rotating coil or armature would be strictly proportiona the intensity of the magnetic field, were it not for the reactions of the current in the armature. Now in a series dynamo, the intensity of the field depends on the strength of the current; and, if the current is kept constant (by adjusting the resistances), the intensity of the magnetic field will also be constant even though the speed of the armature be varied. If therefore the characteristic of a machine be known at any speed, its characteristic for any other speed can be found by the very simple process of increasing the ordinates of the curve in a similar proportion. Take, for example, the case of the Gramme dynamo, of which a characteristic at the speed of 950 revolutions is given in Fig. 156. The characteristic at 1440 could be calculated from it by increasing the ordinates in the proportion of $\frac{1440}{950}$. Thus we see from the lower curve that when the current was 20 amperes the electromotive-force was 79 volts. Then $79 \times 1440 \div 950 = 119{\cdot}7$ volts. The actual electromotive-force observed at the speed of 1440 and with current at 20 amperes was 127 volts. There is a slight discrepancy here, and indeed always; for dynamo machines behave invariably as if a certain number of the revolutions did not count electrically. If the number of "dead turns" (see p. 226) were here reckoned as 140, the number of volts calculated by theory would agree very exactly with that observed.

RESISTANCE IN THE CHARACTERISTIC.

In the characteristic we have volts plotted vertically and amperes horizontally. Now by Ohm's law, volts divided by amperes give ohms. How can this be represented in the characteristic? Suppose, for example, it is required to represent the resistance of the circuit corresponding to some particular current. Let Fig. 158 be the characteristic of the dynamo in question, and it is desired to know what is the resistance corresponding to the state of things at the point marked P. Draw the vertical ordinate P M, and join P to the origin O. The line P O has a certain slope, and the angle of its slope is P O M. Now P M is equal to the electro-

motive-force under consideration, and O M is the cu
Therefore, by Ohm's law,

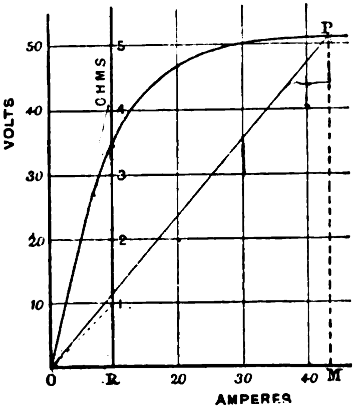
$$\text{Resistance} = \frac{\text{electromotive-force}}{\text{current}} = \frac{\text{P M}}{\text{O M}};$$

but

$$\frac{\text{P M}}{\text{O M}} = \tan \text{P O M};$$

therefore the resistance = tan P O M. Put into word
is :—*The resistance corresponding to any point on the c*
teristic is represented i
characteristic by the tr
metrical tangent of the
made by joining the point
origin. An easy wa
reckoning these tange
shown in Fig. 158. A
point on the horizonta
corresponding to 10 an
erect a vertical line.
drawn from the origin
angle whose tangent i
(namely 45°) would cros
vertical line at a point
site the 10-volt mark.
point may then be ca
ohm, and equal distance
sured off on this line will constitute it a scale of resis
In Fig. 158 the resistance corresponding to point P
characteristic is seen to be about 1·2 ohm on the sc
resistances. Now P is placed at 51·3 volts, and the c
is 43·2 amperes. Dividing one by the other, we ge
ohm. Such calculations are then obviated by the g
construction.

FIG. 158.



METHOD OF REPRESENTING RESISTANCE GRAPHICALLY.

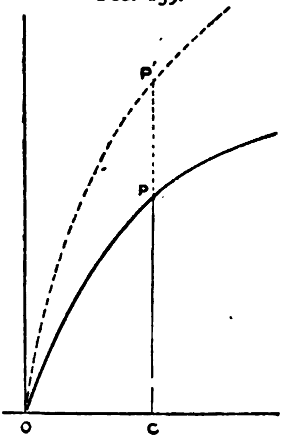
If in the actual dynamo the resistance of the circu
gradually increased, we should have the point P dis
along the curve backwards towards the origin, the vo
amperes both falling off, and the steepness of the lin

increasing. When O P arrived at a certain steepness it would practically form a tangent to that part of the characteristic which is nearly straight, and then any very small increase in the resistance would cause the dynamo to lose its magnetism, from lack of current to magnetize the magnets. The resistance may be similarly represented on the characteristics of shunt dynamos (see Fig. 162); but in this case if the characteristic is drawn for the external current and the external difference of potential, then the resistance so represented will be the external resistance.

RELATION OF CHARACTERISTIC TO WINDING OF ARMATURE AND FIELD-MAGNETS.

Suppose the armature of a machine to be re-wound with a larger number of turns of proportionally thinner wire. What will be the result when rotated at the same speed as before? The resistance will be increased somewhat, and the electromotive-force also will be higher. Let Fig. 159 represent the characteristic of the machine as it was when there were X turns of wire on the armature. How must it be drawn when the number is increased to X′? Let P represent a point corresponding to a certain strength of current. Taking the new armature, let the resistance be varied until the current once more comes to the same value. The magnets are now magnetized exactly as strongly as before; but there are X′ turns of wire cutting the lines of magnetic force instead of X. The electromotive-force will therefore also be greater in the proportion of $\frac{X'}{X}$. Draw therefore P′ C so as to have the proportion P′ C : P C : : X′ : X. All other points on the new

FIG. 159.

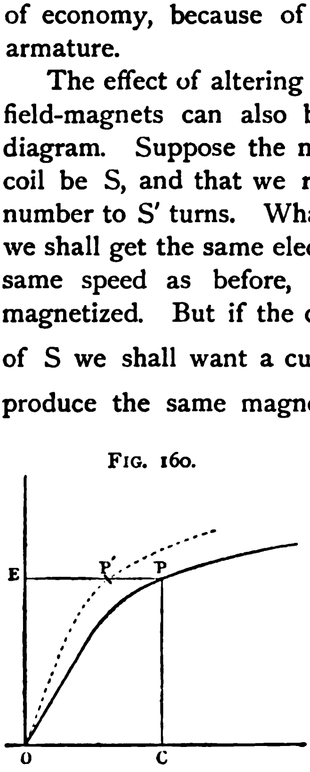


characteristic can be obtained by similarly enlargi
ordinates in the same ratio.

It will be evident from this that increasing the nu
turns of wire in the armature has the same effect as incr
the speed of driving. This shows that *slow speed* dy
(as required for use on ships, &c.) may be made to gi
requisite electromotive-force provided the number of t
wire be relatively increased. This involves, however, a sa
of economy, because of the increase of resistance
armature.

The effect of altering the number of turns of wire
field-magnets can also be traced out on the charact
diagram. Suppose the number of turns in the magn
coil be S, and that we re-wind the machine, increasi
number to S′ turns. What will the result be? In thi
we shall get the same electromotive-force when driving
same speed as before, provided the magnets be e
magnetized. But if the current goes S′ times round i
of S we shall want a current only $\frac{S}{S'}$ as strong as bef
produce the same magnetization. To get the new c
teristic then (see Fig. 160)
PE horizontally. PE = C
the current corresponding t
tromotive-force E. Find P
that P′E : PE :: S : S′
the new characteristic wil
through P′. Similarly, all
points of the new charact
may be determined by re
their abscissæ in a simila
portion.

FIG. 160.



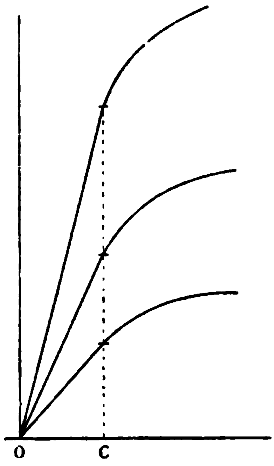
It must be noted that these two processes are not a
sible for the characteristics of shunt-wound machines.

CRITICAL CURRENT OF SERIES DYNAMO.

From the fact that the characteristics for different s
differ only in the relative scale of the ordinates, an imp

consequence may be deduced. The first part of every characteristic for any speed is nearly straight up to a point where for that speed the electromotive-force is nearly two-thirds of its maximum value. When the current is such that the electromotive-force has attained to this value, any very small change either in the speed of the engine or in the resistance of the circuit produces a great change in the electromotive-force, and therefore in the current; therefore, since this critical case occurs always with the same current (see Fig. 161), this current—corresponding to the point on all the curves where the straight line begins to turn—may be called the "critical current" of the dynamo. Each series dynamo has its own critical current, and it will not work well with a less one; for a less one will not adequately excite the field-magnets. It will further be seen that since with each speed the characteristic rises with a corresponding slope, there will be one particular resistance at each value of the speed at which the critical current will be obtained, and the higher the speed the higher may be the resistance. There is no such thing as a critical resistance in a series dynamo: for whether a resistance is critical or not depends upon the speed. *Neither is there any such thing* per se *as a critical speed for a series dynamo;* for whether the speed is critical or not depends on the resistance of the circuit.

FIG. 161.

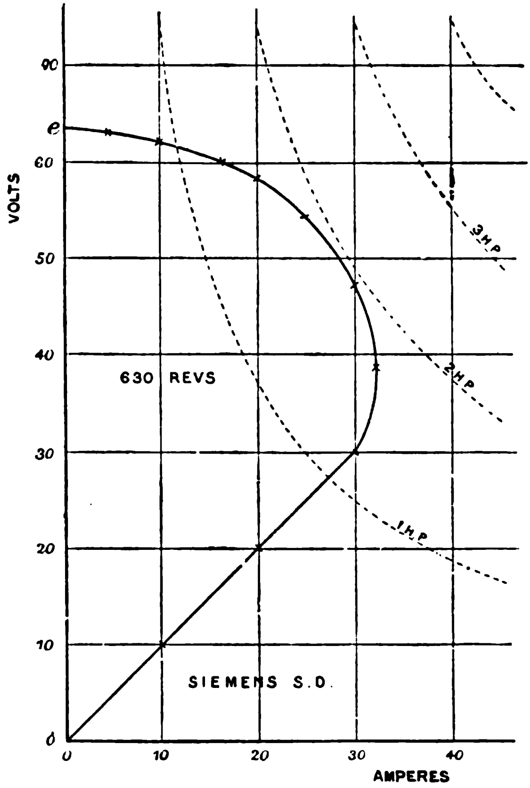


CHARACTERISTIC OF SHUNT DYNAMO.

For the shunt dynamo there are two separate characteristics; the *external characteristic,* in which the quantities plotted are the amperes of current in the external circuit and the volts of potential between terminals; and the *internal characteristic* in which the volts and amperes of the shunt circuit are pl The internal characteristic of the shunt dynamo is similar to the external characteristic of a series dynam shows the saturation of the field-magnets. It is bet plot it with ampere-turns instead of amperes, becaus magnetization depends on the number of turns in th as well as the amperes.

The external characteristic of a Siemens shunt dy (the same described by the late Sir William Siemens

FIG. 162.

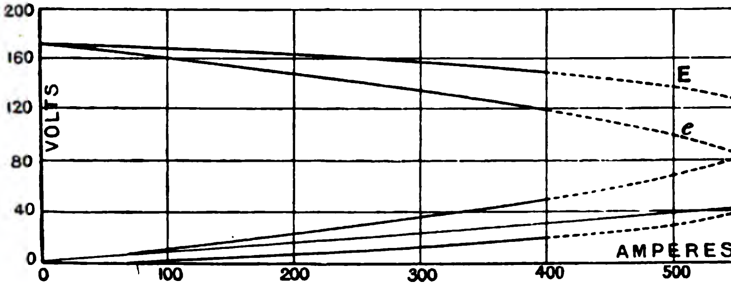


EXTERNAL CHARACTERISTIC OF SHUNT DYNAMO.

the Royal Society in 1880, and by Mr. Alexander Si in the *Journ. Soc. Teleg. Eng.*, March 1880) is given in Fi and the horse-power lines are shown dotted. The utmost power of this machine at 630 revolutions was just under 2 horse-power with a current of 30 amperes, and an electromotive-force of 47·5 volts.

The curve of the shunt dynamo is curiously different from that of the series dynamo. It begins with a straight or nearly straight portion, which turns up in a curve, and eventually returns nearly horizontally to the axis of electromotive-force. The straight portion represents the unstable state when the shunt current is less than its true critical value. The critical external current, if it can be so called, is that current for which the shunt begins to act fully, and in Fig. 162 is about 30 amperes. From this point the shunt current acts with great power, and the electromotive-force here rises very rapidly. The slope of the line which constitutes the first portion of the characteristic represents the resistance which for the particular speed may be termed the critical resistance, and in this case is about 1 ohm. If the resistance of the external circuit becomes in the least degree altered, the electromotive-force and current will alter enormously. Any less resistance will cause the magnets to lose their magnetism at once. Any greater resistance will at once run the electromotive-force up above the critical value—in this case about 30 or 31 volts. If the resistance be steadily increased (and the slope of the line from O to the curve be increased in steepness) the electromotive-force will go on steadily augmenting, and become a maximum when the external resistance is infinite, that is to say when the circuit is completely opened and the shunt coils receive the whole of the electromotive-force of the armature. Fig. 163 depicts the characteristic of a shunt-wound Gramme dynamo capable of giving 400 amperes. In this case the curve e represents the external characteristic, from which the curve E is calculated by adding to the ordinates portions equal to $r_a\, i_a$. As the conductors of the armature could not safely carry more than 400 amperes, the dotted portion of the curve represents results not actually observed. It is instructive to contrast the characteristic of the shunt dynamo with that of the series dynamo (Fig. 153). In the series dynamo also, the first of the characteristic is a sloping line, and the tangent of angle of its slope is also the critical resistance for the g speed. But the series dynamo will only work if the resist of the external circuit is *less* than the critical value, and shunt dynamo will only work if the external resistanc *greater* than the critical value. The contrast is even b shown by drawing a couple of curves in the two cases— characteristics—showing the relation between the potentia terminals and the resistances of the external circuit. Fig. shows this for a series machine, and Fig. 165 for a s machine. The electromotive-force of the one drops sudd when the resistance exceeds 2 ohms; that of the other suddenly when the resistance attains 1 ohm.

FIG. 163.



CHARACTERISTIC OF A SHUNT DYNAMO.

FIG. 164.

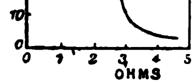
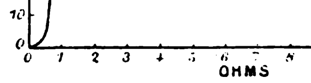
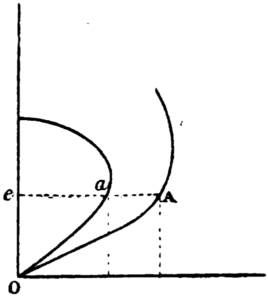


FIG. 165.



In the shunt dynamo the characteristic for a double speed cannot be obtained as in a series dynamo by doubling the heights of the ordinates. For even if at a double speed we adjust the external resistances so that the external current is the same as before, we do not get a double electromotive-force because we do not get the same current as before round the shunt-magnet circuit. And if, on the other hand, we adjust resistances so that we get the same shunt current as before, and therefore a double electromotive-force, we do not get the same external current as before. If, however, we alter the external resistance, taking a larger current externally, so as to reduce the shunt current to its former value, the magnetization will remain as before. In that case the double speed will produce very nearly a double electromotive-force; but the shunt potential may remain as before, the external current being nearly doubled. This is shown in Fig. 166, where *e a* represents the external current in the first case, and *e* A the external current in the second. O A remains a straight line, but at this higher speed the slope is less. From this latter circumstance it may be foreseen that at higher speeds the resistance may be reduced to a lower value before the critical state is reached at which the machine "unbuilds" itself, *i.e.* discharges the magnetism from its field-magnets.

FIG. 166.



CURVE OF TOTAL CURRENT IN ARMATURE.

In the shunt dynamo the current in the armature is equal to the sum of the currents in the external circuit and in the shunt circuit; or

$$i_a = i + i_s.$$

A curve showing the relation between *i* and *e* is easily obtained. In Fig. 167 let the curve O *m i* be the "external characteristic" at the given speed. Take any point on it at that point the potential between terminals in volt measured by the length of *m x* or O *e*, and the curren amperes is measured by the length O *x* or *e m*. Now c the line *s* O at such an angle *s* O *x* that its tangent is equa the resistance of the shunt. Then *e s* represents the cur that will run through the shunt when the potential is O *e* v Add on to the end of *e m* a piece *m n* equal to *e s*; then whole line *e n* represents the armature current i_a when potential has the value O *e*. A set of similar points ma found giving the new curve O *n* i_a required.

FIG. 167.

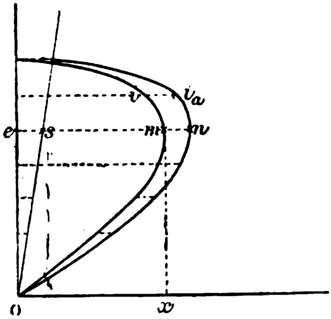
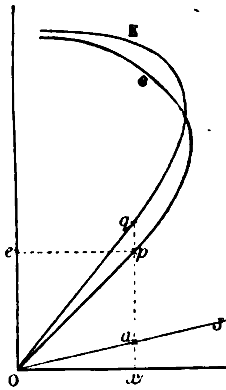


FIG. 168.



TOTAL CHARACTERISTIC OF SHUNT DYNAMO.

If the total electromotive-force E and the total cu i_a be plotted out, we shall obtain the characteristic of total electrical activity of the dynamo.

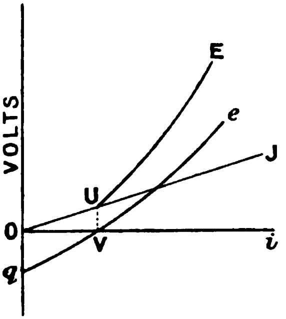
Draw, as in the preceding case, the curve for *e* and i_a. *p* be any point on the curve where the potential is *p x* o and the current *e p* or O *x*. Then draw a line O J at suc angle *a* O *x* that its tangent is equal to the resistanc the armature. Call the point where this cuts *p x*, *a*. T *a x* represents the number of volts required to drive current O *x* through the armature resistance. Add a p

$q p$ equal to $a x'$ to the summit of the line $p x$. Then the height $q x$ represents the total electromotive-force E when the current i_a has the value represented by O x.

CHARACTERISTIC OF SHUNT DYNAMO, WITH PERMANENT MAGNETISM.

If there is residual magnetism in the field-magnets, there will be an electromotive-force induced, even before the shunt circuit is closed. In this case the characteristic would begin at a point p, a short distance along the horizontal axis. In fact the machine behaves as though there were already at work some small electromotive-force (not to be plotted), which had the effect of setting up already a current through the machine, so that the machine excites itself up with currents that are, in the early (and unstable) stages of the magnetization, proportional to the ampere-turns going round the shunt circuit, *plus* some imaginary ampere-turns causing the permanent magnetism. If there is on the field-magnet a second coil, by which an independent magnetization can be introduced, the same kind of result will follow: the characteristic will begin at some point, such as V, the electromotive-force due to the ampere-turns in the shunt being plotted out above O whilst the length O q below represents the part of the electromotive-force due to the ampere-turns (real or imaginary) of the independent magnetism; and O V represents the current which the machine will give when short circuited.

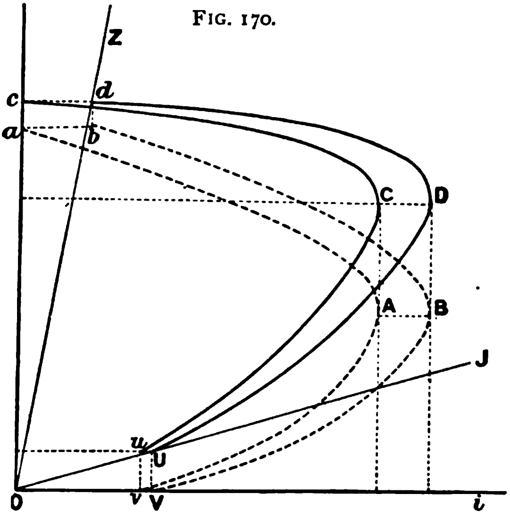
FIG. 169.



There will, in fact, be four curves for a shunt dynamo, namely, those in which the quantities plotted out are respectively e and i, e and i_a, E and i, E and i_a. Of these, the first is the *external characteristic*, and the fourth the *total characteristic*.

These four are depicted in Fig. 170, where they are nar
A, B, C, and D respectively. If D is given, A can be obtai
in the following way:—Let the lines O J and O Z repres
respectively by their slope the resistance of the armature
of the shunt circuit. Then curve B is got from D by deduct
from the ordinates lengths equal to the portions of ordina

FIG. 170.



FOUR CURVES OF A SHUNT DYNAMO.

intercepted by the line O J, and curve C is got from curv
by deducting from the abscissæ lengths equal to the port
of the abscissæ intercepted by the line O Z. Then curv
is got by taking ordinates from B and abscissæ from C co
sponding to any point on D.

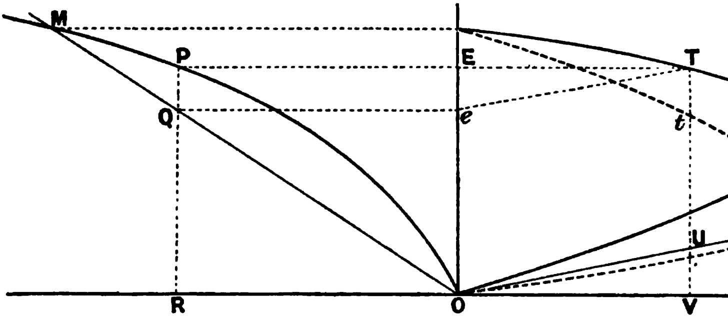
It may be noticed that whilst D B represents the lost v
due to internal resistance of armature, C D represents the
amperes which go round the field-magnets. The lower
resistance of the armature, and the higher the resistance of
shunt, the less will these losses be. In fact, with a well-b
modern machine the four curves lie very close together.

If the curve of magnetization of the machine is known i
easy to determine the characteristic by a geometrical c
struction. The curve of magnetization O P M will show

relation between N and the ampere-turns in the shunt coil, $Z\ i_s$ in our notation.

Let this curve be set out to the left of the vertical axis, then the line O R may be divided out either in a scale representing ampere-turns or in a scale representing amperes, Z divisions of the former scale corresponding to one of the latter scale. The vertical scale plotted out along O E may in like manner represent either N or E; $n\ C \times 10^{-8}$ being the ratio of the readings of the scales. Now set out the line O M, making with O R an angle such that the tangent of its slope corresponds, in the units chosen, to the resistance of the shunt-winding; for example, if the shunt-resistance be 16, the line will pass through a point the ordinate of which represents 16 volts and the abscissa 1 ampere. Let this line meet the curve of magnetization at M. If we consider any point P on the curve, its ordinate P R will represent, according as we please, either the effective magnetism when the magnetizing current is O R, or the whole number of volts E induced in the armature; and the part of the ordinate Q R will represent the difference of potential e. Clearly then P Q will represent $E - e$ that is to say, the volts lost in the armature, which are equal to $r_a\, i_a$. Now if on the right of the diagram we lay out a line O J at such an angle that the tangent of its slope represents the armature resistance r_a, then if V be taken so far along the horizontal axis that V U = P Q, the length O V will represent i_a. The most convenient construction is to project points P and Q across to E and e, and from e draw e T, parallel to O U, meeting E T in T; then drop a perpendicular from T giving the points t, U, and V, where T t = U V. T will be a point on the curve connecting E and i_a; t a point on the curve connecting e and i_a. From the latter curve the external characteristic can be got as shown on p. 252. Of these hyperbolic curves the lower limb which returns towards O represents the unstable portion corresponding to the lower part of the magnetic curve. From the existence in the curves of a maximum value of i_a, where the curve turns round on the extreme right, it must not be inferred that the machine can yield this maximum current; on the contrary, the maximum current that the machine can safely give depends on the section of its armature wires these are—in the best machines—not intended to carr current under such conditions. The working part of the c is usually the top part (Fig. 171), and it will be obvious the construction that the smaller the internal resistanc

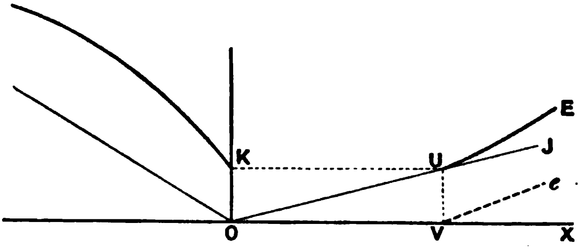
FIG. 171.



farther will the curve extend to the right and the more n horizontal will the tops of both curves be; a good s dynamo, with very little internal resistance, being *nearly* regulating for constant potential.

If there be no initial or residual magnetization, the c will both pass through O; but neither of them will do

FIG. 172.



there is initial or residual magnetization. In that case curve of magnetization will commence above O at some p such as K, Fig. 172, and the lower ends of the two curve E and *e* will end at points so far to the right that the w U V = K O. With almost every shunt dynamo it is fo that if descending values of *e* are taken (at any giving speed) *e* becomes zero, whilst *i* has still a definite value.

It will also be noticed that the limiting value of E depends on the slope of M O, that is to say, on the resistance per turn of the shunt coil ; any diminution of the resistance per turn will raise E by forcing up to a higher degree the magnetization corresponding to a given value of *e*.

CONTRAST BETWEEN SERIES DYNAMO AND SHUNT DYNAMO.

The difference between series dynamos and shunt dynamos in their behaviour when the resistance of the current is increased or decreased, has already been touched upon in p. 263. In electric lighting, dynamos are usually required either (*a*) to supply glow-lamps arranged in parallel, in which case the dynamos must maintain a constant potential at the mains, or else (*b*) to supply arc-lamps arranged in series, in which case the dynamo is required to yield a constant current. In the case where the potential is to be constant, the current will vary with the number of lamps in parallel; in the second case, where the current is to be constant, the electromotive-force must vary as the number of lamps in series.

To understand the applicability of series or shunt dynamos to either of these tasks, it will be convenient to construct (either from experiment or from theory) comparative curves. In the case of parallel distribution, every additional lamp switched on across the mains adds to the conductance of the circuit an amount equal to its own conductance (*i.e.* equal to the reciprocal of its own resistance). It is therefore expedient to plot out together the values of *e* and of $\frac{1}{R}$. This has been done in Fig. 173 for two dynamos, for each of which the maximum value of *e* was the same. It will be seen that for neither a series nor for a shunt machine does the value of *e* remain constant as the number of lamps across the mains is increased. The shunt machine gives the more nearly constant potential, but falls off as the number of lamps is increased.

In the case of single-circuit distribution to lamps in s every additional lamp adds to the resistance of the circuit in this case it is expedient to plot out together the value and R. Fig. 174 shows the result for the two kinds of mac

FIG. 173.

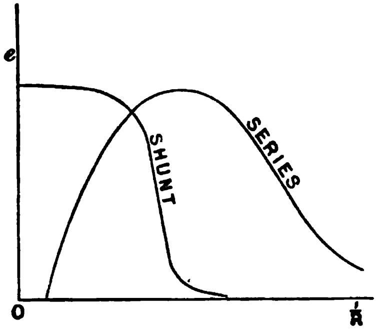
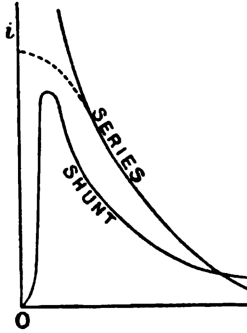


FIG. 174.



It will be seen that neither machine gives anything like a stant current; but for the shunt machine there is just one stage, namely, when its current is at the maximum, wher value is more constant than anything that the series dyr can give. The dotted part of the curve corresponds to the of a series dynamo so designed as to have a drooping ch teristic (like Fig. 157, p. 256), which gives more nearly moderately small resistances) a constant current. But abundantly clear that something more than a simple seri simple shunt machine is requisite to give a real self-regul machine for either purpose.

FURTHER USE OF CHARACTERISTICS.

The following examples of the further use of character are taken from Dr. Hopkinson's paper in the *Proc. Inst. Engineers* for April 1880:—

To Determine Lowest Possible Speed of Dynamo running an Arc Lamp.

It appears that with the ordinary carbons, and at ordinary atmos pressure, no steady arc can exist with a less difference of potentia about 40 volts; and that in ordinary work, with an arc about ⅛ inch long, the difference of potential is from 45 to 50 volts. Assuming the former result about 40 volts for the difference of potential, the use of the curve of electromotive-forces may be illustrated by determining the lowest speed at which a given machine can run and yet be capable of producing a short arc. Taking O as the origin of co-ordinates (Fig. 175), set off upon the axis of ordinates the distance O A equal to 20 volts; draw A B to intersect at B the negative prolongation of the axis of abscissæ, so that the ratio $\frac{O\,A}{O\,B}$ may represent the necessary metallic resistance of the circuit. Through the point B thus obtained draw a tangent to the curve, touching it at C, and cutting O A in D. Then the speed of the machine, corresponding to the particular curve employed, must be diminished in the ratio $\frac{O\,D}{O\,A}$, in order that an exceedingly small arc may be just possible.

FIG. 175.

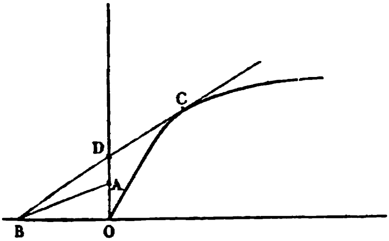
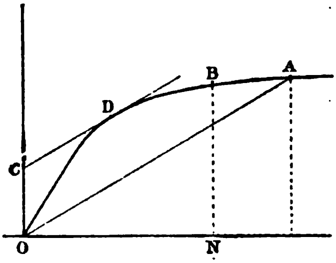


FIG. 176.



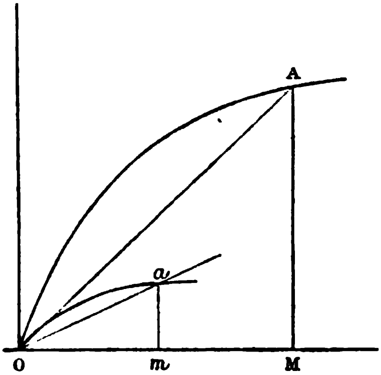
Use of Characteristic to Explain Instability of Arc Light.

The curve may also be employed to put into a somewhat different form the explanation given by Dr. Siemens at the Royal Society respecting the occasional instability of the electric light as produced by ordinary dynamo-electric machines. The operation of all ordinary regulators is to part the carbons when the current is greater than a certain amount and to close them when it is less; initially the carbons are in contact. Through the origin O (Fig. 176) draw the straight line O A, inclined at the angle representing the resistances of the circuit other than the arc, and meeting the curve at A. The abscissa of the point A represents the current which will pass if the lamp be prevented from operating. Let O N represent the current to which the lamp is adjusted; then if the abscissa of A be greater than O N, the carbons will part. Through N draw the ordinate B N meeting the curve in the point B; and parallel to O A draw a tangent C D, touching the curve at D. If the point B is to the right of D, or farther from the origin, the arc will persist; but if B is to the left of D, or nearer to the origin, the carbons will go on parting till the current suddenly fails and the light goes out. If B, although to the right o very near to it, a very small reduction in the speed of the machi suffice to extinguish the light.

Relation of Characteristic to Size of Machine.

Suppose that a certain dynamo of a given construction has characteristic the curve O *a* (Fig. 177). What will be the charact of a dynamo built of precisely the same type, but with all its dimensions doubled? The surfaces will be four times as gre volume and weight eight times as great. There will be the same n of turns of wire, but the length will be doubled and the cross-s quadrupled, and therefore the internal resistances will be halved.

FIG. 177.



resistances were adjusted so as to give the same current as befo new machine would have only half the intensity of field of the sma But if adjusted to give the same intensity of field as before, the c will be doubled.

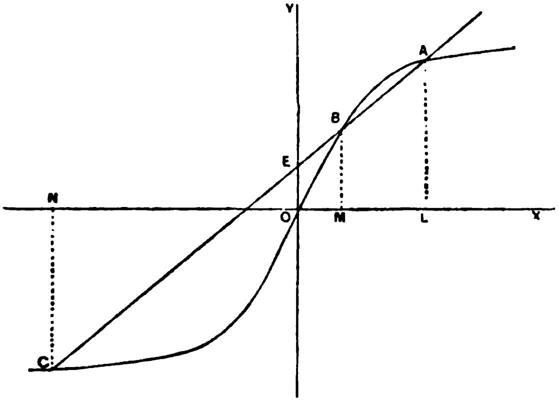
Now as the area of the rotating coils is increased fourfold, the be four times as many lines of force cut (at the same speed), and the the electromotive-force will be four times as great. But we only w the current doubled. That is to say, the resistance will have doubled if the field is to be of same intensity. To represent this s things, take the point *a* on the characteristic of the small machin draw the ordinate *a m*. Draw O M, double O *m*, and at M ere ordinate A M four times the length of *a m*. The new characteristi pass through A. Also the resistance—the slope of O A—will be that of O *a*. The points *a* and A are similar points with respect saturation of the iron of the magnets; and it is this which determin practical limits to the economic working of a dynamo of given t a given speed. Hence we see, with quadrupled electromotive-forc double current, the electric energy evolved per second will be eight times as great as with the smaller machine when worked up to an equal saturation limit. These points may be compared with the discussion of the relation of size to efficiency on p. 117.

Application of Characteristics to Dynamos used in Charging Accumulators.

The following problem is of great practical importance :—*Suppose a dynamo is used for charging an accumulator, and is driven at a given speed, what current will pass through it?*

Dr. Hopkinson has given a solution of this problem for the case of a series dynamo. Draw the total characteristic of the dynamo (Fig. 178) for the given speed. Along O Y set off O E to represent the electromotive-force of the accumulator, and through E draw the line C E A, making an angle with O X such that its tangent represents the resistance of the whole circuit, including the accumulators. This line will cut the characteristic in the points B and A ; and, if the characteristic be repeated backwards, in C also. This negative branch of the characteristic is simply the characteristic of the dynamo when the current through it is reversed, and its electromotive-force therefore also inverted. Then O L represents the actual current in the circuit ; O M represents an unstable current which might exist for a moment ; and O N represents the current which would traverse the circuit were the accumulators to overpower the dynamo and reverse it, as indeed frequently happens when series dynamos are so used. For it will be observed that if, as is the case when accumulators are reaching their full charge, their electromotive-force were to rise, or the resistance of the circuit to increase in consequence of heating, the

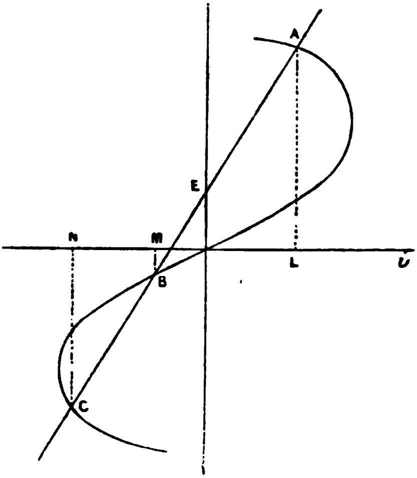
FIG. 178.



inevitable result would be to diminish A L, the effective electr
force, and to diminish the current O L, so that the magnetism of t
magnets will also drop, and the point A will be brought neare
position of instability at the bow of the curve.

With the shunt dynamo the case is different. Let Fig. 179 r
the characteristic of the shunt dynamo, the external current being
along O X, and the total electromotive-force along O Y. Draw
C E A as before. Then it cuts the positive branch at A, and O
current in the main circuit. If, now, either the counter electr

FIG. 179.



force of the accumulators or the resistance of the circuit increa
effect will be to move the point A to a higher point on the curv
charging current O L may diminish, but the shunt current will i
or the effective electromotive-force A L will be increased. T
with the shunt dynamo there will be no likelihood of the accun
overpowering and reversing the dynamo.

CHAPTER XI.

CONSTANT POTENTIAL DYNAMOS.

Conditions of Supply.—The conditions of electric supply necessitate that the output of the dynamo should be regulated correspondingly. For some purposes—as for feeding a system of incandescent lamps in parallel—the current must be supplied to the mains at an absolutely *constant potential*, or, as some popularly phrase it, at a *constant pressure;* that is to say, the difference of potentials between the mains at the terminals of the dynamo, or at the lamps, must be constant. This, of course, implies that the current delivered by the machine shall vary exactly in a ratio inverse to that of the resistance of the external circuit, increasing, as the resistance is diminished, by adding to the number of lamps across the mains of the circuit. But we have seen that, owing to two causes—(1) internal resistance, (2) demagnetizing reactions of armature—the volts at the terminals at full load fall short of the value they would have (at the same speed and magnetization) at zero load. The *lost volts* increased with the load. Hence means must be taken to compensate for the lost volts if the supply is to be maintained *at a constant pressure.* If a dynamo is to supply lamps at, say 60 volts, the pressure must not be allowed to fall to 58 or 57 volts when all the lamps are at work.

For some other purposes, as for supplying a set of arc lamps connected in a simple series, or for charging a number of sets of accumulators in different houses, or for running a number of motors in different places on one line, it is necessary to maintain in the line an absolutely *constant current*, no matter how many or how few lamps or motors may be at work. This, of course, means that when the resistance of the main circuit is increased by the switching-in of more lamps, the dynamo must of itself put forth a proportionate in of electromotive-force.

The two ends to be attained by regulation are therefo only distinct, but incompatible with one another; a dy cannot possibly keep its electromotive-force constant, a the same time vary it in proportion to the varying resi of the external circuit. The two systems must theref kept absolutely apart. They are adapted to entirely di cases of electric distribution. Their theory is different the practical modes for carrying them out are different a

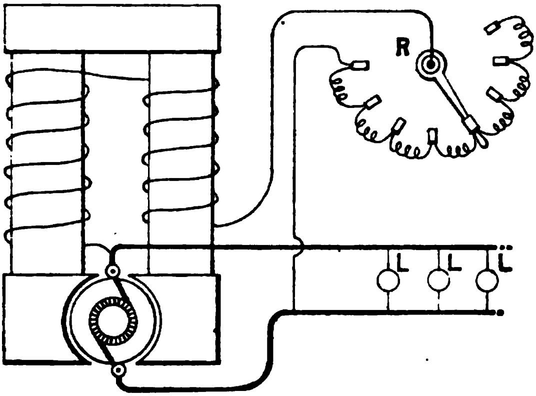
Constant-current machines, as required for arc-lig and for special glow lamps in series, are describ Chapter XVII. The present chapter will deal only machines for supply at constant pressure.

There are various ways of governing dynamos so maintain either a constant potential or a constant cu Some of these methods involve hand regulation; others, matic switching in or out of resistances, to vary the exci of the field-magnets; others, automatic adjustment o brushes; and others, electrical governing of the speed. chapter on Regulators deals with these. Let it be not the first place that the voltage of a given dynamo depen shown by the fundamental equation (p. 47), on three thi the speed, the number of armature-windings, and the ma flux: hence it follows that any one of these might be u control the output of the machine. The speed can be ch by purely mechanical contrivances. The number of eff armature conductors can be changed by shifting the br forward beyond the neutral point. The magnetic flu be varied by altering the magnetizing force that excit magnetism, or by changing the disposition of the mag circuit. All these devices for governing dynamos have used.

In cases of isolated plant it may be convenient to a governor (such as Willans's or Richardson's) to so var speed in accordance with the demands on the circuit maintain a constant electric pressure; but this is not factory when the engine has other work than driving a dynamo. Hence, methods have been preferred which admit of the maintenance of a constant speed of driving. Throughout this chapter this condition will be assumed to hold good; and as a purely magnetic method of regulation is but little used, we need only deal here with the methods that depend on the varying magnetizing forces. Some of these methods are adapted for hand-control, whilst others are automatic.

Edison's Regulator.—In Edison's method of supplying mains at a constant potential a shunt dynamo is employed, a variable resistance, or rheostat, R, being introduced into the shunt-circuit (Fig. 180). A lever moved by hand, whenever the potential rises or falls below its proper value, makes contact on a number of studs connected with a set of resistances, and thus controls the degree of excitation of the field-magnets. A similar device has been used in several other systems. To make the arrangement perfect the variable resistance should be automatically adjusted by an electromagnet the coils of which are an independent shunt across the mains. Edison has indeed used such a device. The shunt dynamo, if well constructed, is, as shown on p. 270, nearly constant in its voltage; the pressure at the terminals falls off very little at full load. With such a dynamo, but a small increase of

FIG. 180.



EDISON'S METHOD OF REGULATING.

exciting power is needed to make up for the lost volts load. The regulating rheostat is equally applicable separately-excited machine.

Self-regulating Dynamos.—Seeing that an increa magnetism is required to compensate for the lost vol dynamo may be made self-regulating if the increase of c in the main circuit, which causes the drop in the volts, made automatically to cause also a compensatory augn tion of the magnetism. If, in addition to the excitin which produces the requisite initial magnetization of the magnet, there is provided a compensating coil of wire enough to carry the main current, the desired end v attained. If the machine is shunt-wound to begin wit a compensating coil in series with the armature is thus the combination is usually termed a "compound" wi The term "compound dynamo" having been introduc Messrs. Crompton and Kapp to signify a dynamo with series and shunt-winding, by analogy with the engineer "compound engine" for a steam-engine working witl high- and low-pressure cylinders. Compounding is not ever, the only mode of self-regulation; for a comper series-coil is equally applicable to any well-designe tinuous-current dynamo in which the initial magnet independently or constantly excited. The following binations are possible :—

(*i.*) Series regulating coils + permanent magnets to the field initially, with an independent co magnetization.

(*ii.*) Series regulating coils + an independent curren lating in separate coils round the field-m to produce an independent constant mag tion.

(*iii.*) Series regulating coils + an independent curr culating in the main circuit (and generated by a battery or by an independent ma dynamo) having the effect of partly exciti field-magnets, with an independent constan netization.

(*iv.*) Series regulating coils + shunt-magnet coils supplied by a portion of the current of the machine itself thereby partly exciting the field-magnets, with an independent and nearly constant magnetization.

(*v.*) For alternate-current dynamos, coils in series with the main circuit cannot be used, but they may be compounded by providing them with regulating coils supplied with a current derived (by a suitable transformer) from the main-circuit currents, and proportional to them, the derived currents being first sent through a suitable commutator to rectify them. The independent magnetization may be derived either from an auxiliary exciter, or from a separate coil or group of coils in the armature, or, in fact, by another transformer, the primary of which is placed across the mains as a shunt, in either of the latter cases the current being properly commuted.

Theoretically, several other self-regulating combinations are possible; for example, a machine with a long armature lying between two separate field-magnets, one independently excited, the other in series; a series machine with unsaturated magnets combined with a (quasi-independent) series machine with over-saturated magnets on the same shaft; a series machine having two sets of field-magnet poles at different leads, one of the sets of poles being the series-excited set, the other excited independently, or in shunt circuit; &c.

THEORY OF SELF-REGULATION.

In considering the theory of self-regulation we shall proceed as follows:—First find an expression for the potential at the terminals of the dynamo. This will, in general, consist of three terms. Secondly, we shall consider these three terms as to whether their factors are constants or variables. Then, having ascertained which of the terms contain variable factors, we must consider what conditions

must be laid down (such as prescribing a particular s
a particular number of windings) in order that the ter
taining variable factors shall disappear. These conditi
be embodied in an "equation of condition," which will
discussed. In general it will be found that if the s
prescribed beforehand, there will be a certain "c
number of regulating coils to be deduced; or, on th
hand, if the number of regulating coils is prescribed
hand, there will be a particular or "critical" speed at
self-regulation holds good.

It is possible to treat the theory either algebraic
geometrically. Both methods will be here used.

Case (i.). Series Regulating Coils + Permanent Mag
If the field-magnets are partly permanently magn
or if there are permanent steel magnets in addi
the electromagnets, giving a partial permanent field
pendent of that due to the current in the circuit, w
denominate the number of magnetic lines in this indep
field as N_1.

Now the fundamental equation of the series dynam

$$E = n\,C\,N,$$

and the difference of potential between the terminals,
wise called the pressure, is shown on p. 227 to be

$$e = E - (r_a + r_m)\,i.$$

But N, the number of magnetic lines that pass throu
armature at any instant, is made up of two parts, the
nent independent part N_1, and a part depending up
current i, and equal to

$$\frac{4\pi S i \div 1}{\Sigma \dfrac{l}{\mu A}};$$

where S is the number of turns in the regulating coi
length of the magnetic circuit, A its cross-section, and
average value of the permeability (see p. 318) between t

extreme values that it has when i is zero and when i is at its maximum. If for brevity we write

$$4\pi \Big/ \Sigma \frac{l}{\mu A} = q,$$

we may then write the variable part of N as $q S i$; and therefore,

$$N = N_1 + q S i;$$

and we get, as the complete expression for e,

$$e = n C (N_1 + q S i) - (r_a + r_m) i,$$

or

$$e = n C N_1 + n C q S i - (r_a + r_m) i.$$

The expression on the right-hand side of this equation consists of three terms, of which the first contains the speed and two constants as factors. The last two contain a variable, the current, and one of them also contains as factors the speed n and the number of regulating coils S. If S is prescribed beforehand, then the particular speed at which the dynamo is self-regulating will be clearly that speed at which the expression for e will contain nothing but constants. If n is prescribed beforehand, then we must vary S so as to eliminate the terms that contain the variable factor. Since the two last terms are of opposite sign, it is clear that by varying S or n, or both, the value of $n C q S$ may be made numerically equal to $r_a + r_m$. Then at the constant speed, which we will call n_1, the last two terms will cancel one another out, or,

$$n_1 C q S i - (r_a + r_m) i = 0.$$

That is to say, S and n_1 must be such that

$$n_1 C q S = r_a + r_m. \qquad [XIII.]$$

This is the equation of condition.

If the condition laid down in this equation is observed, then the last two terms for e disappear, and we have simply,

$$e = n_1 C N_1 = \textit{a constant.}$$

Having thus proved that, at the given speed, e is a constant, it is worth while to enquire what it is that determines the value

of *e*. Clearly *e* is directly proportional to N_1, the indep
and permanent field magnetism. Therefore, we can
that the dynamo, still driven at the given speed, sha
any potential we please, within limits, provided we alte
the requisite proportion.

Suppose that the speed is prescribed by mechanic
siderations, then the proper or critical number of reg
coils is given by the expression

$$S = \frac{r_a + r_m}{n C q}.$$

This is instructive. The higher the internal resistanc
dynamo the greater must be the number of the reg
coils in series, if it is to be self-regulating.

Returning to the equation of condition, we will
in the second form—

$$n_1 C q S = r_a + r_m,$$

which gives us as the value of the critical speed,

$$n_1 = \frac{r_a + r_m}{S} \cdot \frac{1}{C q}.$$

This shows us that, if the series coils are prescribed th
be a certain critical speed of self-regulation, and this
will be higher the greater the internal resistances are.

Lastly, we may write the last equation in the fol
way,

$$\text{critical speed} = \frac{\text{total internal resistance}}{\text{number of turns of series coil}} \times \text{a q}$$

depending only on the armature windings and on the ma
circuit and its working permeability within the range fo
regulation is required.

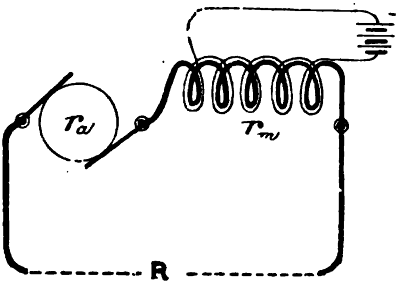
So far we have assumed that the only cause of
pressure that needed to be compensated for was that
internal resistances. But the drop of pressure due
demagnetizing action of the armature is in modern ma
a consideration of even more importance. To take a
of this action we must remember that if the angle of le

known, the demagnetizing belt of conductors (see p. 89) will be that comprised within an angle of 2 λ, namely $C\lambda/90°$. And each such conductor carries $\frac{1}{2}i$ amperes, making the demagnetizing ampere-turns $C\lambda i \div 180°$. Or, if the number of conductors within the angle λ is called D, the demagnetizing ampere-turns will be $2D \times \frac{1}{2}i = Di$. This is for drum machines: for ring machines the product must be doubled. As however, these turns are situated over the armature, whilst the compensating coils are wound on the field-magnet, their action will be greater in proportion approximately to the leakage coefficient v (see p. 183). Hence we shall have to increase S, the series coils, from the value found above to the value

$$S = \frac{r_a + r_m}{n_1 C q} + D v. \qquad \text{[XV.]}$$

Case (ii.). Series Dynamo + Separately-exciting Coils (see "*Series and Separate,*" Fig. 44, p. 58).—In this case there is an independent magnetism due to a current carried round the field-magnets in separate coils, and providing a part of the field magnetism. The connexions are shown in Fig. 181.

FIG. 181.



If we call the number of magnetic lines due to the independent excitation N_1, the same argument holds good as in the preceding case, and the same conclusions. N_1 will not, however, be really a constant, for the effect of the introduction of a constant amount of magnetizing force will vary with the degree of saturation resulting from the *whole* magnetizing force. If, however, the average working permeability throughout the range of regulation is taken into account in the calculation of N_1 as well as in that of S, then any falling-off

in the effect of the independent exciting current is implicitly pr
for.

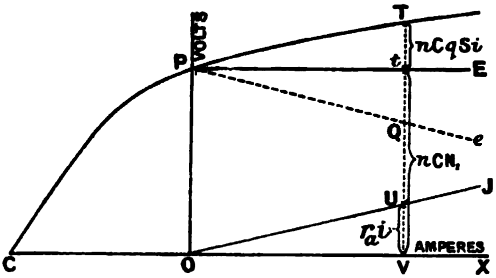
Messrs. Wright & Kapp have accomplished the same end as C
using one coil only in the main circuit, to which coil, however, a b
or the circuit of a separate dynamo, is applied as a shunt. M.
has made a somewhat similar suggestion.

Geometrical Demonstration of Cases (i.) and (ii.).

On p. 230 it was shown how the values of the potent
terminals fall off in magneto and separately-excited dyn
as the current increases, e always being less[1] than E
amount equal to $r_a i$.

To represent the facts, let O X and O P be taken a
axes for plotting out amperes and volts, and let O P
sent the electromotive-force ($E = n_1 C N_1$) due to the
manent or independent magnetism, as measured whe
current is running through the armature. Now, assu

FIG. 182.



that the armature reactions are small enough to be negl
E will at constant speed remain the same with all cur
but e will drop. From O set off the line O J at an
such that its tangent represents the internal resistance o
machine. Now consider the case when the current i ha
particular value corresponding to the length O V. The h

---

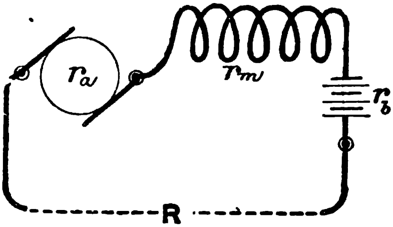
[1] This is illustrated in Fig. 150, p. 232, where the curve e shows the dr
to this cause, and the curve B the actual drop, due chiefly to this cause and
to the demagnetizing reactions going on in the armature.

U V will be the drop in the external electromotive-force; for U V = tan U O V × O V = $r_a i$. Cut off from t V a portion, tQ = U V, and Q V will represent e. While the curve for E and i is approximately a horizontal line, the curve for e and i (the external characteristic) drops, as shown by the dotted line. Any point on the e curve can be got from the E curve by simply deducting from the height a piece equal to the corresponding width across the triangle J O X. Now it must be obvious that if when the E curve is horizontal the e curve slopes downward, we must use an E curve that slopes upward by a precisely equal amount, if we want to get a horizontal e curve; that is to say, if we want to get constant potential. How are we to get an upward sloping E curve? Remember that at a given speed, n_1, the value of E is n_1 C N_1, where N_1 means that the magnetic circuit has somehow (either permanently or by a separate current) been excited up to such a degree that N_1 lines go through the armature. The same plotting that serves for volts will serve for values of N by choosing the appropriate scale; or, O P may represent N_1. Therefore P is a point on a curve of magnetization, which will rise still higher if only we put on more ampere-turns of excitation. Therefore all that is required to be done is to put on the magnets a coil in series, having such a number of turns S that the ampere-turns S i will have the effect of raising the magnetism in the right proportion; in fact, so that T t shall be equal to U V. We have now got an E curve which slopes up—not quite a straight line, to be sure, but such that when we subtract the volts required to drive the current through the armature resistance, we get an e curve that is approximately level.

Comparing the algebraic and geometric methods, we see that tV corresponds to n_1 C N_1; T t to n_1 C q S i; and U V to $r_a i$, or if the resistance of the added series coil is included in the slope of the line O J, U V will correspond to $(r_a + r_m) i$.

Case (iii.). Series Dynamo + Independent Electromotive-force thrown into the Main Circuit.—This really comprises two cases: where the independent constant electromotive-force is due to a battery, and where it is due to a separate magneto machine driven at a c speed ("Series and Magneto," see p. 282). The argument same, however, for both cases. Fig. 183 will represent eithe

FIG. 183.



We have here as the whole electromotive-force of the comb E, the electromotive-force of the armature, plus E_b the inde electromotive-force thrown in from the battery or magneto n The difference of potential between the terminals, which always denominated as e, will be got by subtracting from that part of the electromotive-force which is devoted to current i through the internal resistances, which are now r_a, r_b; so that we have

$$e = E_b + E - (r_a + r_m + r_b)\, i.$$

Now $E = n\, C\, q\, S\, i$; therefore, in order to make the l terms cancel one another and leave e a constant, we must speed the value n_1 such that

$$n_1\, C\, q\, S = r_a + r_m + r_b,$$

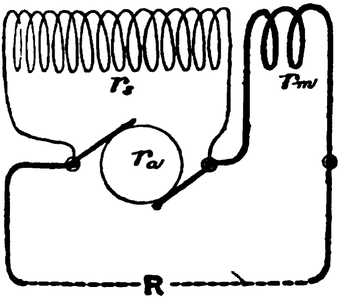
which is the equation of condition. In this case,

$$e = E_b.$$

This proves that in this case, too, the constant potentia terminals is identical with that due to the independent ex Of course this does *not* mean that the dynamo does no wor the contrary, it means this: that when the resistance of the circuit is infinitely great, so that the dynamo does no work, only electromotive-force in the circuit is that due to the inde source.

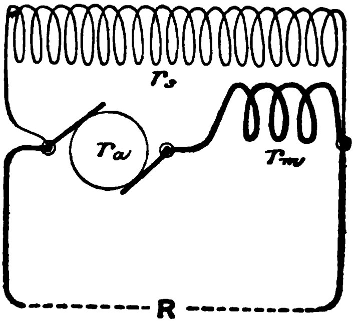
Case (iv.). Series Regulating Coils + Shunt E Coils: "Compound Winding."—The compound-wound d may be regarded as either a series dynamo to whic shunt windings have been added, so as to provide an initial magnetization, or as a shunt dynamo to which some series windings have been added to compensate for the drop of potential at the terminals. There are two possible methods of connecting the shunt coils to the dynamo, and the proportions differ slightly in the two cases. In the "short-shunt" method (see p. 60) the shunt coils are joined as a shunt to the armature part of the dynamo only, being connected across from brush to brush. In the "long-shunt" method the shunt coils are connected across the terminals of the machine, and may, therefore, be regarded either as a shunt to the external circuit, or as a shunt to the armature and series coils together. In the former arrangement the current through the shunt is not constant, because the potential at the brushes ϵ is not the e; and though e may remain fairly constant, ϵ does not, but increases when the external circuit's resistance decreases. In the latter arrangement the current through the shunt is constant if e is constant, and the case becomes one analogous to those already discussed, of an independent constant excitation. The connexions of the short-shunt method are indicated in Fig. 184. Since in a well-designed dynamo r_a is very small, r_m will also be very small, for few regulating coils in series are required. Moreover, as the shunt resistance r_s is

FIG. 184.



COMPOUND-WINDING:
SHORT-SHUNT.

FIG. 185.



COMPOUND-WINDING:
LONG-SHUNT.

relatively very great, the shunt current will be r small, and it makes very little difference therefore the shunt is connected across the brushes or ac terminals of the main circuit. The connexions of t shunt arrangement are as shown in Fig. 185.

The calculations for the two cases are practically i and involve the same kind of arguments. That for lo is a little more simple, and is accordingly given.

We have then

$$E = n\,C\,N\,;$$

$$e = E - (r_a + r_m)\,i_a\,;$$

and as the magnetism depends on the total nu ampere-turns circulating around the field-magnet, write,

$$N = q\,(Z\,i_s + S\,i_a)\,;$$

where q has the same signification as before (p. 283),

$$= \frac{4\pi}{10} \Big/ \Sigma\,\frac{l}{\mu A}\,;$$

or more strictly is the variable number representin various stages of magnetization, the numerical ratio N and the total number of ampere-turns for the r circuit of the particular dynamo. It is of course best by reference to such a diagram as Fig. 105. For the purpose it is necessary to consider (1) the value whi when the external current is zero, and when t excitation is that due to the shunt, namely $Z\,i_s$ ampe this may be called q_0; and (2) the value which q has current in the armature is at the maximum for w dynamo is intended to be used. If the maximum c called x, this value may be called q_x. Then, as the varies from o to x, the corresponding values of N v from

$$N_0 = q_0\,Z\,i_s$$

to

$$N_x = q_x\,(Z\,i_s + S\,x).$$

Now between these two limits, which we may call the range for which the dynamo is required to be made self-regulating, q will have intermediate values, and one of these must be selected for use in the formula. The value $\frac{1}{2}(q_0 + q_2)$ will not be far from a fair average. Let this average value be denominated q_1 in the equations which follow. Then from the three preceding equations we have

$$e = n \mathrm{C} q_1 \mathrm{Z} i_s + n \mathrm{C} q_1 \mathrm{S} i_a - (r_a + r_m) i_a .$$

Now here we have three terms, the first containing, as factors, the speed (which may be kept constant), and the shunt current i_s which will be made constant if e can be made constant; the second contains the speed also as a factor; the second and third both contain the variable current i_a. The two variable terms are of opposite sign. Now e cannot possibly be a constant, when two of its terms contain a variable as factor, unless the coefficients of that variable factor are such that they make those two terms cancel one another; e cannot be constant unless either the speed n or the windings S, or both, are so adjusted as to fulfil this. But these can be adjusted and even with a given value of S a particular value of the speed n_1 can be found, such that

$$n_1 \mathrm{C} q_1 \mathrm{S} = r_a + r_m . \qquad \text{[XVI.]}$$

This is then one of the two equations of condition; and then if the speed be given, the critical number of series-turns will be

$$\mathrm{S} = \frac{r_a + r_m}{n_1} \cdot \frac{1}{\mathrm{C} q_1} .$$

Or, if S is prescribed, the critical speed will be

$$n_1 = \frac{r_a + r_m}{\mathrm{S}} \cdot \frac{1}{\mathrm{C} q_1} .$$

If this condition be observed, then e will be constant and have the value

$$e = n_1 \mathrm{C} q_1 \mathrm{Z} i_s .$$

But this would leave e indeterminate. But we may reflect that though this equation might not give us the value of e,

there will nevertheless be a determinate value for i
the same value that e would have when there is n
taken from the dynamo at all, but when it is runnin
circuit only. Under these conditions the value of e

$$e = n_1 \mathrm{C} \mathrm{N}_o - (r_a + r_m) i_s ;$$

or, since here q has the value q_o,

$$e = n_1 \mathrm{C} q_o \mathrm{Z} i_s .$$

But $e = r_s i_s$, whence we get

$$n_1 = \frac{r_s}{\mathrm{Z}} \cdot \frac{1}{\mathrm{C} q_o} .$$

Comparing this value of n_1 with that obtained in
equation of condition, we get

$$\frac{r_s}{\mathrm{Z} q_o} = \frac{r_a + r_m}{\mathrm{S} q_1} ;$$

whence, finally, as the *second* equation of condition,

$$\frac{\mathrm{Z}}{\mathrm{S}} = \frac{r_s}{r_a + r_m} \cdot \frac{q_1}{q_o} .$$

As q_o is proportional to μ_o the permeability whe
no external current, and q_1 proportional to the av
meability μ_1 for the range of working between ze
and maximum current, it follows that if there were
tion of saturation, $q_1 \div q_o$ would equal 1. In t
editions of this work, wherein the theory of compou
expressly based upon the supposition that ther
saturation—or in other words, that the permeability
stant—the formulæ obtained were admittedly inc
this reason. Dr. Frölich found for a certain Siem
and shunt dynamo,

$$\frac{\mathrm{Z}}{\mathrm{S}} = 17 \cdot 7, \text{ whereas } \frac{r_s + r_a}{r_a + r_m} = 61 \cdot 9 .$$

From which it is clear that μ_o must have been about
as great as μ_1; in other words, this machine had an i
quantity of iron in its magnets or armature core, o

This dynamo must have been both badly designed and of low efficiency; r_s ought to have been not 61·9, but at least 300 times as great as $r_a + r_m$. It will be noticed that, apart from the demagnetizing action of the armature, the amount of excitation to be provided for by the series coils is always proportional to the resistances that are in the main circuit and *internal to the points for which the constant difference of potential is desired;* this renders it possible in a case where the mains leading from the dynamo to the lamps are long so to compound the dynamo by adding more coils in series as to give a constant potential, not at its terminals, but at the distant point of the circuit where the lamps are to be used. This is a most valuable circumstance in all cases where the lamps are far from the dynamo, as in the lighting of mines from machinery at the surface; for then by *over-compounding,* one can obtain a constant pressure, not at the terminals of the dynamo, but on the mains at some point in the midst of the lamp-network. There is another advantage in over-compounding, namely, that when the full load comes upon a machine, the engine, however carefully governed, generally slows down a little, tending to produce a further drop in the voltage.

To compensate for the demagnetizing action of the armature, additional turns are required in the series coil, as explained above on p. 284. To make the last set of formulæ complete S should be replaced by S — D *v*.

ARRANGEMENTS OF COMPOUND WINDING.

Compound windings may be arranged in several different ways. If wound on the same core the shunt coils are sometimes wound outside the series coils: less frequently the series coils are outside the shunt. In some of Siemens' dynamos they are wound on separate frames and slipped on side by side over the same core. In other cases, where (as in Siemens' usual patterns) the pole is at the middle of the magnet core, one end of the core may carry the shunt coils, the other the series; or both the coils on one of the cores may be series coils, and both those on the other, shu In Elihu Thomson's machines the series coils are wo frames close over the armature. In some of Siemens' n with double magnetic circuits, the series coils were only on the cores adjoining that horn of the pole-piec would otherwise be weakened by the reaction of the ar with the effect that the distortion of the field was corrected. It is advisable to keep down the resistanc series coils, as they will form part of the main circuit the additional resistance necessitated by winding the coils of larger diameter is not altogether a disadvant shunt coil. In the former editions of this work the mendation was made to wind the series coils nearer than the shunt coils. With the better magnetic circ employed in dynamos, this advice has ceased to ha weight. If the magnetic circuit through the ironw good, the position of the coils makes little difference.

PRACTICAL PROCESS FOR COMPOUNDING.

It is clear from the foregoing paragraphs that the co machine, when run on open circuit, with only the current flowing, must give the same potentials at its te as it is to give as a compound machine. Hence this the following practical process for compounding. armature of the machine be run at the proper speed by mechanical considerations, and let a voltmeter be at the terminals. Two experiments are then ne First, by means of temporary coils, having a known of turns wound on the field-magnets, and furnish measured currents from some accumulators or dynamo, ascertain the number of ampere-turns that wi to excite up the magnets to this point. From this Z determined; for it is known beforehand that r_s mus least 300 or 400 times (or sometimes as much as 100 r_a; and therefore i_s is really known beforehand. S put into the main circuit some resistance to repres maximum load of lamps, and while the machine is ru its proper speed, ascertain, using still the temporary coil and accumulators, how many ampere-turns of excitation are needed in total when the machine is doing full work, subtracting from this the value of $Z\, i_s$ obtained in the first experiment, the remainder gives the number of ampere-turns which the series coil must furnish, and as the maximum current is known, S can at once be calculated. The same process suits for *over-compounding*, the excitation at full load being raised until the volts at terminals rise to the higher number of volts that will allow for the drop in the leads.

DESIGN OF CONSTANT POTENTIAL MACHINES.

It is obviously of importance in such machines that the iron parts should be so designed that (1) the characteristic should be as nearly straight as possible in that portion of it corresponding to the working range of currents for which regulation is desired; (2) that it should not turn down. Consequently it is of importance in such machines that there should be just so much iron in the magnetic circuit that the current due to the shunt should carry the initial magnetization over the knee of the curve of magnetization; and that the reactions due to the armature currents should be small; or in other words that there must not be too much copper on the armature, and that the field-magnets should be relatively powerful. Also, of course, the resistance of the armature should be kept as small as possible.

TIME REQUIRED FOR COMPOUNDING.

Machines which have very solid field-magnets cannot suddenly respond by a change in magnetism to a sudden change in the demand for current, in consequence of the currents induced in the solid iron which oppose and delay changes in its magnetic state. Hence, such machines, even though compound-wound, fail to keep the pressure constant, as they cannot act quickly enough. For such work as supplying current to an electric tramway, an over-compounded dynamo with *laminated* field-magnets is the best generator.

CHARACTERISTIC OF COMPOUND DYNAMO.

In the original theory of constant potential m
devised by Marcel Deprez, the argument was based up
absence of saturation, and the presence of an initia
pendent magnetization. The following was the argu
Deprez. If there is a permanent excitement of mag
quite independent of that due to the main-circuit coils
dynamo, the characteristic (Fig. 186) will not start from
from some point above it depending on the amount o
pendent magnetization and on the speed. Let the s
point be P. O P is the electromotive-force between te
when the main circuit is open, but there is no external
until the circuit is closed, and then the characteristic
the usual fashion from P to Q. Draw O J at the prope
to represent the resistance of the armature and serie
together. Now consider a line O E drawn at such an
that the tangent of its slope represents the total res
of the circuit at any particular moment. Then E x is t
electromotive-force at that moment, and a part of this
to $a x$, will be employed in driving the current O x t
the resistance of armature and series coils. The rem
part E a represents the difference of potentials betwe
terminals of the external circuit. So the problem r
itself into this: how to arrange matters so that E
always be of the same length as O P, no matter how m
how little the line O E may slope. Clearly the only wa
this is so to arrange the speed of the dynamo that th
from P to Q shall be parallel to O J. If the speed is r
exactly to the right amount the inclination of the cha
istic will be equal to that of the line O J. Then, as sh
Fig. 187, the potential between the terminals will be co
It will be seen that this agrees with the deductions
at in the algebraic treatment of the question: namel
the critical speed is proportional to the internal resis
and that the constant difference of potential E a is eq
that due to the independent magnetization O P at the
speed.

It should also be noticed that if the part of the characteristic be not straight, that is to say, if the field-magnet cores are becoming saturated, the regulation cannot be perfect. If the line P Q be curved, then the potential for large currents will not be equal to that for small currents. If, in the practical process for winding the magnets, the coils have been wound so as to make *e* the requisite number of volts, both on open circuit (*i. e.* at O P), and at another point (say at Q J), when the dynamo is feeding its maximum load, then there will in general be a slightly greater potential for intermediate loads, owing to the slight convexity of the curve between P and Q.

Fig. 186.

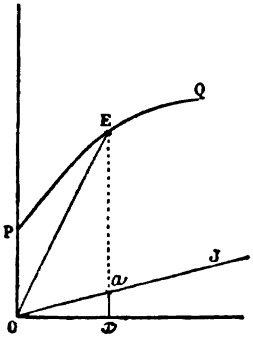
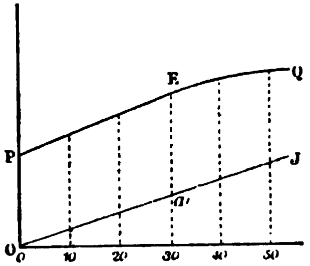


Fig. 187.



The above argument holds good whether the independent excitation be due to permanent magnetism or to a combination with separately-exciting coils (see pp. 58 and 59), or to shunt-exciting coils. In the latter case O P represents the potential at terminals due to shunt excitation alone.

The case of the "compound" dynamo is worth looking at from another point of view also. On p. 264 two curves—not characteristics—are given, showing the relation of electromotive-force to external resistance in a series machine and in a shunt machine. One begins at a certain height and falls when the resistance has attained a certain value; the other begins low and rises when the resistance has attained a certain value. It is conceivable that if a dynamo were wounc both shunt and series coils, so that each worked up t same potential at the same speed, and so proportione the number of ohms at which one fell should be the sa that at which the other rose, then the compound m

Fig. 188.

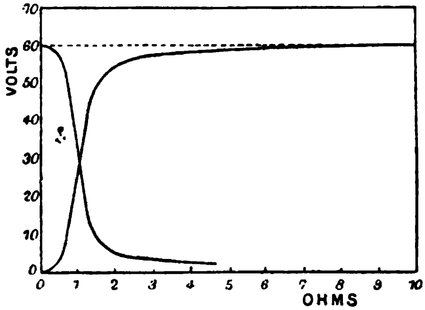
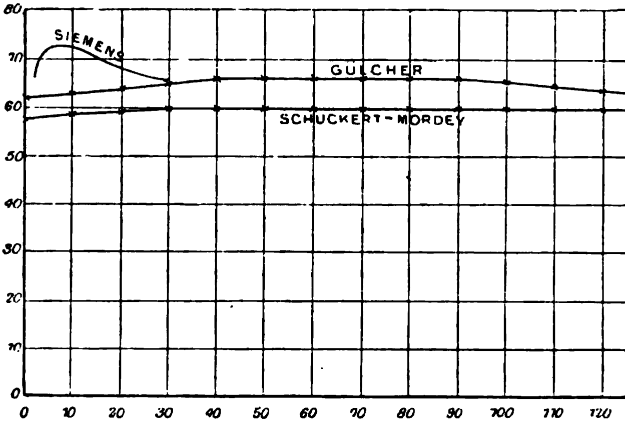


Fig. 189.



External Characteristics of Compound-wound Dynamo

should, as indicated in Fig. 188, give as a result of the c winding, a constant potential. It remains to be seen h this is attained in practice.

EXTERNAL CHARACTERISTICS OF SELF-REGULATING DYNAMOS.

Simultaneous observations of the external current i and the external potential e enable us to plot the external characteristic; which in a perfectly self-regulating dynamo would be a horizontal line. The curves given in Fig. 189 relate to an old Siemens dynamo,[1] a Mordey "Victoria" dynamo[2] (see p. 498), and a Gülcher machine (see p. 503).

If the number of regulating coils in series is too small, the characteristic will fall as the current rises; if too large, will rise slightly from the beginning near the origin (see Fig. 189). This latter case, however, is not always a disadvantage, for with machines worked singly on an engine the speed often falls in consequence of imperfect governing as the load on the dynamo is increased.

Esson's Observations.—Some observations by Mr. W. B. Esson, in the *Electrician* of June 1885 are worthy of consideration in connexion with recent theory. Mr. Esson asks why is it that compound dynamos wound so as to be self-regulating for a given speed, regulate fairly well at any speed within considerably wide limits? To explain this peculiarity he observes that in no dynamo is the quantity or quality of the iron such that the saturation effect can be neglected. If the magnetism were strictly proportional to the ampere-turns of excitation, there would be literally a critical speed. The approximate rule $\frac{S}{Z} = \frac{r_a + r_m}{r_s}$ gives the number of series coils much too low, for when the shunt coil has already excited a certain degree of magnetization, the series coil cannot produce its proportionate increase. In a series machine (designed to give a current of 20 amperes), the electromotive-force added to the machine by increasing the exciting current from 5 to 10 amperes is much greater than the electromotive-force added by increasing the current from 10 to 15 amperes. Again, a 100-volt machine (self-regulating), in which therefore the shunt gave excitement enough for 100 volts on open circuit, had series coils upon it which were able, when the shunt was removed and the full current on, to give 60 volts between terminals. The value of the series coil to excite magnetism is diminished as the excitation due to the shunt is increased. All this is, of cours to the diminution in permeability of the iron of the mach the degree of saturation increases. From this it follows certain relation must subsist between the speed of the machi the degree to which the magnets are excited by the shunt coil. the magnetism furnished by the shunt coil also depends c speed, and increases with it. If, therefore, at one speed this re is such as to produce self-regulation, the relation will be equally true at other speeds. At the high speed the relative va the series coils is less, and at the low speeds it is greater; b sum of the two effects may be constant. At speeds lowe the normal speed, the potential is lower when there is a large ance in circuit than where there is a small resistance in circui speed higher than the normal, the potential falls as the resista diminished. Mr. Esson deduces from the foregoing consider certain practical hints as to how to improve the regulation dynamo whose potential rises either when many or when few are in circuit.

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[1] See Richter in *Elektrotechnische Zeitschrift*, April 1883.

[2] See *Journal Soc. of Arts*, March 7, 1884.

Engineers desiring further information on compound wind dynamos, are referred to a series of articles in the *Electrician*, in by Mr. Gisbert Kapp; also to two articles by Mr. Esson in the *Elec* of June 1885. Articles by M. Hospitalier in *L'Électricien*, and by Uppenborn in the *Centralblatt für Elektrotechnik*, should also b sulted: and the student should above all read the series of published by Dr. Frölich in the *Elektrotechnische Zeitschrift* for and a still more remarkable paper by Professor Rücker in the *sophical Magazine* of June 1885. Some account of these was giv the Appendices of the third edition of this book. The latest contrib to this question are by C. Zickler, *Centralblatt für Elektrotechn* 264, 1887, and M. Baumgardt, *ib.* x. 281, 1888; and by Dr. Loui in the *Electrical World*, xvi. 383, 1891.

CHAPTER XII.

ON WINDING OF ARMATURES. THEORY OF CONNEXIONS.

THIS Chapter is devoted to the theory of the ways of joining up and combining the conductors on the armatures of dynamos. Workshop details concerning materials and modes of construction are considered in Chapter XIII. At present we deal with the important preliminary considerations which apply to design rather than to construction.

It has been pointed out, on p. 41, that excepting for arc-lighting machines, which usually have "open-coil" armatures, continuous-current dynamos are provided with closed-coil armatures, that is to say armatures on which, whether wound according to the ring, drum, or disk type, the winding is re-entrant on itself, the current dividing between at least two paths and reuniting as it leaves the armature. For machines with two poles there are but two such paths, the current dividing once only. But for multipolar machines there may be either two, or more than two, such paths; with one, or more than one, bifurcation of the current. The electromotive-force of the machine will obviously depend on the mode of connexion of the conductors, as to how many active conductors are connected in series. Hence the necessity of understanding the theory of armature winding.

To connect up rightly the conductors on an armature so as to produce the desired result is a simple matter in the case of ring winding, for continuous-current machines, whether of bipolar or multipolar type. It is a much less easy matter in the case of drum windings, especially for multipolar machines. Often there are several alternative ways of arriving at the same result; and the fact that methods which are electrically

equivalent may be geometrically and mechanically difi
makes it desirable to have a systematic method of tre
the subject.

In Chapter III., pp. 41 to 45, we have already consi
the elementary structure of ring, drum, and disk arma
Those elements would suffice for the consideration of
armatures coiled with only a few turns of wire. But wh
proceed to the design of large machines, or of machines
are to be wound so as to give potentials as high as 4
more volts, further information is needed. For exa
suppose we have designed a 4-pole machine having a
armature with 100 bars spaced around its periphery, all i
layer, numbered consecutively from 1 to 100, and we
to complete the end-connexions; we must be able to in
the workman as to the order in which they are to be conn
Is he to connect the front[1] end of bar No. 1 right acr
bar No. 50, or No. 49? Or is he to connect it across a q
of the periphery, and, if so, is it to join No. 25 or No.
to No. 75 or No. 76? To which return bar is he to co
the back end of the bar? And which bars are to be conn
down to the commutator?

The object of the present Chapter is to give inform
on these points. Brevity is essential; and much more
have been written. Those who wish to go further should
sult the writings of Hering,[2] Arnoux,[3] Fritsche,[4] Weym
and Arnold,[6] as well as sundry patent specifications to
reference will be made.

As remarked above, there is generally little trou
understanding a ring winding, provided the distinction bet
a right-handed and a left-handed winding is comprehe
So leaving for the present a further discussion of multi
ring windings, we pass on to consider drum winding.

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[1] "Front" end means the end where the commutator is; armature
always most conveniently regarded from this end.

[2] Hering: *Principles of Dynamo-Electric Machines*, New York, 1891.

[3] Arnoux: *l'Électricien*, xii. 1888, pp. 737, 774, 827.

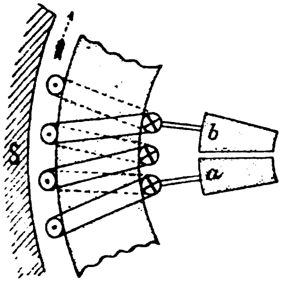
[4] Fritsche: *die Gleichstrom-Dynamomaschine*, Berlin, 1889.

[5] Weymouth: *The Electrician*, xxv. Nov. 7 to Dec. 19, 1890.

[6] Arnold: *die Ankerwickelung der Dynamomaschinen*, Berlin, 1891.

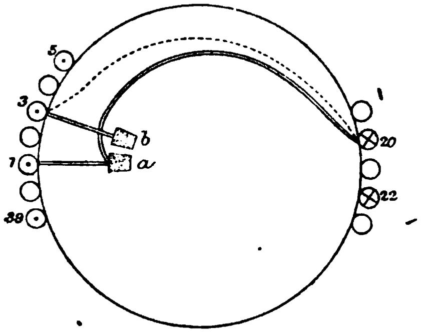
The first point to settle is what constitutes the difference between a right-handed and a left-handed winding. In the case of ring armatures there is no doubt. Fig. 190 shows one section of a ring, the direction of the currents being indicated in the same way as on p. 77, Figs. 61 to 63. As we pass right-handedly around the circle from *a* to *b* we follow a right-handed spiral path, the current climbing (as explained on p. 64) to the positive brush at the top. (A left-handed coiling, such as Fig. 31, p. 39, would give the positive brush at the bottom, unless either the rotation or the polarity of the dynamo were reversed.) Now consider Fig. 191, which depicts one element or section of a drum-winding having 40 external conductors.

FIG. 190.



RIGHT-HANDED RING WINDING.

FIG. 191.

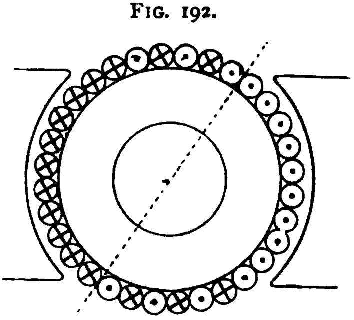


RIGHT-HANDED DRUM WINDING.

Starting from *a* to climb to *b*, and noting the direction of the currents in the conductors, it is obvious that *a* must be connected by a spiral connector across the front end of the drum to one of the descending conductors such as No. 20, from which at the back end another connector must join it to one of the ascending conductors, such as No. 3, where it is led to *b*, thus making one right-handed turn. Now examine Fig. 206, p. 318, Fig. 208, p. 319, and Fig. 212, p. 322. They are all left-handed, the last having eight turns of wire in one section. Note in passing that if the back connector in Fig. 191 from No. 20 to No. 3 had passed under the shaft, instead of over it, the winding would still have been a right-handed winding.

The next point is to ascertain over how many con these spiral connectors ought to pass. We connectec (*viâ* the bar *a*) to No. 20, and then back to No. 3. I any reason why No. 20 should have been chosen a No. 21, or No. 19, or No. 18? To understand this w consider the question of commutation in the conducto whole, and also remember that there are two paths t the windings from brush to brush. This is a drur 40 conductors in one layer: and there will be 20 bars commutator. Remember that the induced electror forces will be directed from back to front in the con rising on the left, and from front to back in those desc on the right. It is natural to think that each conducto to be joined to the one that lies diametrically opposite In that case No. 1 should be joined to No. 21, No. 2 to and so forth. But this will not do. Each conductor side needs a return conductor on the other side. Th numbers may be looked upon as the returns for th numbers. Hence No. 1 ought not to be joined to N Shall it be joined to No. 20 or to No. 22? or shall we to No. 18? Nos. 20 and 22 lie on either side of the o is diametrically opposite, and electrically it makes no dif which we select of these two. If we are going to use connector which returns over the shaft (as in Fig. 191), t a slight saving of copper if we select No. 20. If th connector returns under the shaft, either may be taken. copper will be saved if we select No. 18 and return ov shaft, as the spiral connectors will be shorter. But if w connect across a short chord of the circumference, inst taking the chord nearest to the diameter, we risk counter electromotive-forces in the turns that are in from brush to brush. On the other hand, as Swinbur shown, connecting across a short chord has the advanta the armature has a less powerful demagnetizing action. effect of winding across a chord subtending the span pole-piece is shown by Fig. 192, in which it will be se belt of demagnetizing conductors between the pole tips replaced by a belt, in which the currents flow in two op directions, thus neutralizing one another. In no case should the chord subtend a less angle than that subtended by the polar face. The rule then for connecting is as follows for a simple 2-pole drum armature. The number of conductors C being an even number, the front connector must cross from any conductor to that which is ½ C ± 1 further on (or ½ C ± 3 for shortening the chord); and the back connector must lead back to the next conductor but one. In the following winding table the letters F and B stand for *front* and *back*, and the letters U and D stand for *up* and *down*, meaning toward the front end, and from the front end respectively. From this it will be seen that starting with conductor No. 1, we follow *down* it to the back, there connect it to No. 22, then come *up* to the *front*, then come (connecting to a bar of the commutator in passing) to No. 3, go down this, and connect across the back to No. 24, and so on. The overlap is in all cases 21. At last we come to No. 20, up which we return to the front and connect (*viâ* the last bar of the commutator) to No. 1.

FIG. 192.



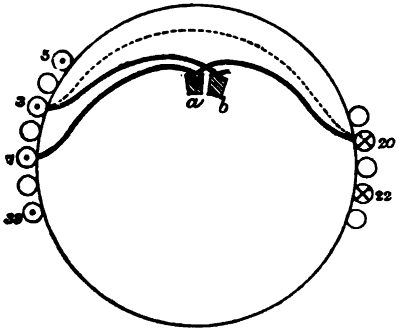
EFFECT OF CHORD WINDING.

WINDING TABLE. 2-POLE DRUM. 40 CONDUCTORS.

F	B	F	B	F	B	F	B	F
D	U	D	U	D	U	D	U	
1	22	3	24	5	26	7	28	
9	30	11	32	13	34	15	36	
17	38	19	40	21	2	23	4	
25	6	27	8	29	10	31	12	
33	14	35	16	37	18	39	20	

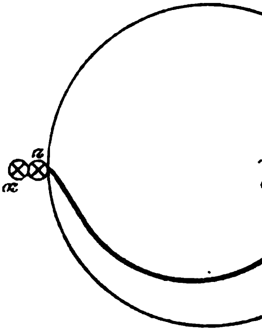
Simple as the matter may seem, the problem l
connect across the end of the drum from one condu
that which is next but one, or next but three, to the di
cally opposite conductor, is not altogether easy wh
mechanical and electrical difficulties are taken into a
To shorten the length of the long spiral connectors, an
the end connectors more symmetrical, the arrangeme
cated in Fig. 193 is sometimes used. The spirals a

FIG. 193.



DRUM WINDING WITH TWO SETS OF SPIRAL CONNECTORS.

FIG. 194.



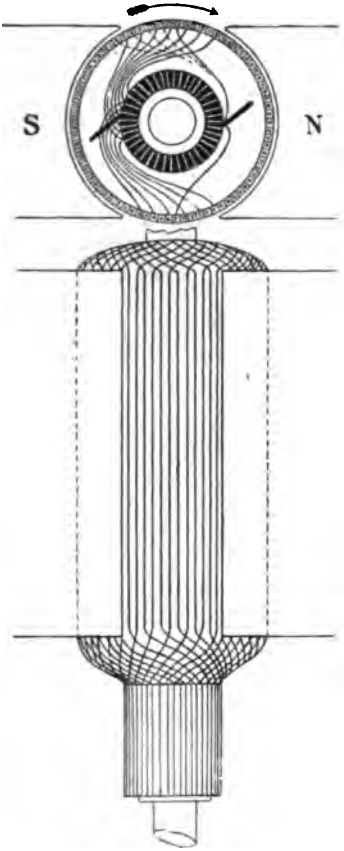
TWO-LAYER DRUM W

arranged in two layers one over the other, as in Fi
p. 364, with the effect that the commutator has virtuall
turned through about a quadrant, so that the + brush
on the left instead of at the top. This mode is adopte
Edison-Hopkinson armatures amongst others. It h
advantage that all the spiral connectors front and ba
be made of same size.

If, however, the conductors are arranged in two
one over the other, the windings may be made a
diameter, the last turn being brought across to th
in the same layer. The conductors of the outer lay
answer instead of the intermediate members of th
layer set. In Fig. 194 the end of No. 1 is brought to *a*;
it spirals round to No. 21, which is connected across th
to No. 3, and so on. Fig. 195 shows how the 80 condu

the Edison-Hopkinson armature (see p. 519) are connected, there being in reality two layers of 40 each, and a 40-part commutator.

FIG. 195.



DRUM WINDING OF EDISON-HOPKINSON DYNAMO.

DEVELOPED WINDING DIAGRAMS.

If one tries to draw all the connectors of a drum winding the lines cross and occasion confusion. There is therefore a great advantage in adopting a mode of representation, originally suggested by Herr Fritsche,[1] of Berlin, in which the armature winding is considered as though the entire s had been developed out on a flat surface.

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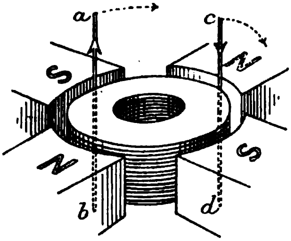
[1] *Centralblatt für Elektrotechnik*, ix. 649, 1887.

Consider first Fig. 196, which is a partial sketch o pole machine laid on its side. The core, which may after wound either as ring or as drum, lies between poles of alternate polarit copper rod *a* is placed pa the axis to represent one armature conductors, and posed to move along th space right-handedly past pole, it will cut the magnet entering that pole. By t given on p. 22, the induced motive-force in it will be u Another conductor *c* pass N pole will have induced downward electromotive-force. If one was to attem picture such as this to show twenty or more conduct their respective connexions, the drawing would be u gible. Accordingly we have to imagine ourselves at the centre, and the panorama of the four poles ar to be then laid out flat, as in Fig. 197. It will be notic the faces of the N and S poles are shaded obliqu distinction.[1]

Fig. 196.



Sketch of 4-pole Field.

Now in an actual machine there are many armatu ductors spaced symmetrically around, and these hav grouped together by connecting wires. In the case windings the wires which connect the active conducto gap-space pass through the central aperture in the rin they are removed from the magnetic field. Supp simplicity, we have a ring armature of only 12 tur rned the other way. The winding *d*–7–12 does not return .once to *e*, but goes on to *i*, whence another element *i*–17–4–*e* es on in a sort of zig-zag wave. These are both drum ndings, the corresponding tables being as follows :—

---

[1] I choose these oblique lines for the following reason. If instead o *a b* (representing a conductor), a narrow slit in a piece of paper were laid drawing of the pole-face, and moved as the dotted arrows show towards the slit in passing over the oblique lines will cause an apparent moti direction in which the current tends in reality to flow. It is easy to which way the oblique lines must slope ; for those on a N pole-face slop to the oblique bar of the letter N.

INDING-TABLE FOR FIG. 200.
(LAP-WINDING.)

F	B		F
+ *a*	1	6	*b*
b	3	8	*c*
− *c*	5	10	*d*
d	7	12	*e*
+ *e*	9	14	*f*
f	11	16	*g*
− *g*	13	18	*h*
h	15	2	*i*
i	17	4	*a*

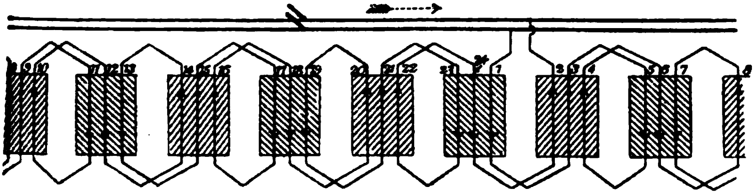
WINDING-TABLE FOR FIG. 201.
(WAVE-WINDING.)

F	B		F
a	1	6	*f*
f	11	16	*b*
b	3	8	*g*
− *g*	13	18	*c*
c	5	10	*h*
h	15	2	*d*
d	7	12	*i*
i	17	4	*e*
+ *e*	9	14	*a*

It will be noted in passing that whilst with this particular umber of conductors (18) the lap-winding results in four arallels of coils, and needs four brushes, the wave-winding esults in two parallels, and requires two brushes only.

Before going on to other drum-windings it may be re- arked that the same distinction between lap-windings and

FIG. 202.

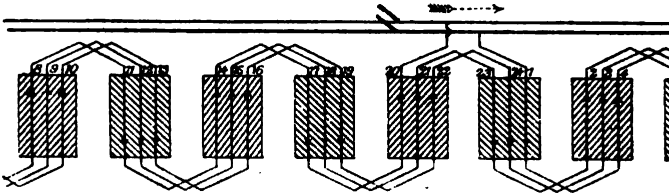


ALTERNATE CURRENT MACHINE: LAP-WINDING.

wave-windings is applicable to alternate current machines. These are usually multipolar. In Fig. 202 is an 8-pole lternator with lap-winding, each "element" or set of loops

extending across the same breadth as the "pitch" or
from centre to centre of two adjacent poles. Only
ductors have been drawn; and it will be noticed t
successive loops are alternately right-handed and left-
In Fig. 203 is shown the same alternator with a wave-

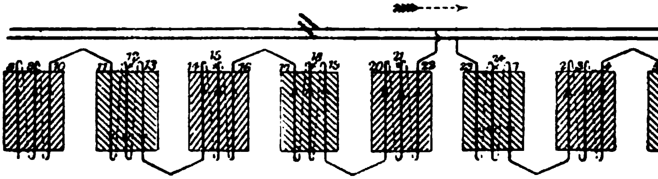
FIG. 203.



ALTERNATE CURRENT MACHINE: WAVE-WINDING.

The electromotive-force of the two machines would
cisely the same; the choice between the two me
connecting is here purely a question of mechanical con
in construction and cost. A ring-winding suitable for
currents is developed in Fig. 204; also for an 8-pole
should be compared with Figs. 202 and 203.

FIG. 204.



ALTERNATE CURRENT MACHINE: RING-WINDING.

WINDING FORMULÆ FOR CLOSED COIL ARMAT

General formulæ for connecting—applicable ch
drum-windings—have been given by Hopkinson
Arnold. We shall follow the latter in the main.
stand for the number of conductors as arranged aro

armature core. Let p stand for the number of pairs of poles so that the actual number of poles is $2p$. Let b stand for the number of active conductors in any one "element" of the winding, s for the number of sections, and c for the number of bars in the commutator. Clearly in ring-windings b is the number of turns in a section. Let the numerical step by which one advances in connecting up the conductors from one section to another be called y (for example, if No. 8 section is connected to No. 15, then $y = 7$). This number y, since it represents the number of spaces between the sections that are bridged over, may be called the "*spacing*." It must always be, relatively to s, a prime number, otherwise the winding will not be re-entrant as a closed coil. If they have a common factor (as, for example, $s = 36$, $y = 27$, where the common factor is 3) there will be as many *independent* circuits.

Such independent circuits have been used by Weston, and by Messrs. Siemens Bros. Armatures so wound require broad brushes covering at least two segments of the commutator.

Arnold's formulæ connecting these quantities are

$$y = \frac{1}{p}\left(\frac{C}{b} \mp a\right);$$
$$C = b\,(p\,y \pm a);$$

wherein a is a certain whole number (often = 1) on the value of which depends the number of bifurcations of the current through sets of coils that are in parallel with one another. The number of neutral points on the commutator will be always $= 2a$. In applying the formulæ we have several cases to deal with.

(*i.*) *Parallel Grouping.* As we have seen in the case of an ordinary ring in a 4-pole field, there will be four rows of $\frac{C}{4}$ coils each in parallel with one another. In a 2-pole field there are two rows of $\frac{C}{2}$ each. In a 12-pole field we should have 12 rows of $\frac{C}{12}$ each, in parallel. As we have seen above in the case of the 4-pole ring with spiral-winding, eacl such rows may be considered as constituting a s 2-pole armature. It is also so for drum armatures if with lap-windings, but not if with wave-windings. T cases stand thus :—

(*a*) *With Spiral-winding or Lap-winding* write formula $p = 1$ and $a = 1$, and apply it to conductors lying between two poles of simila

(*b*) *With Wave-winding* write $a = p$; that is there must be as many bifurcations of the cu there are pairs of poles. In a 6-pole machine and the current will bifurcate at three poi three negative brushes), going through six paths to the three positive brushes (or to tl connexions that lead to the positive brush).

(*ii.*) *Series Grouping.* For this, seeing that the only bifurcates once, $a = 1$, whatever the mode of In the case of 2-pole machines the series groupi parallel grouping are the same thing—there are two coils in parallel with one another, and the winding either a wave-winding or a lap-winding; or, as will be spiral-winding may be used for ring machines. For machines the same holds good. For machines havir poles than four, however, the only possible cases o grouping are wave-windings.

(*iii.*) *Mixed Groupings.* There are several possibl of mixed lap- and wave-windings, corresponding t where $a > 1$ or $a \gtrless p$.

As examples for verifying these formulæ we ma the following :—

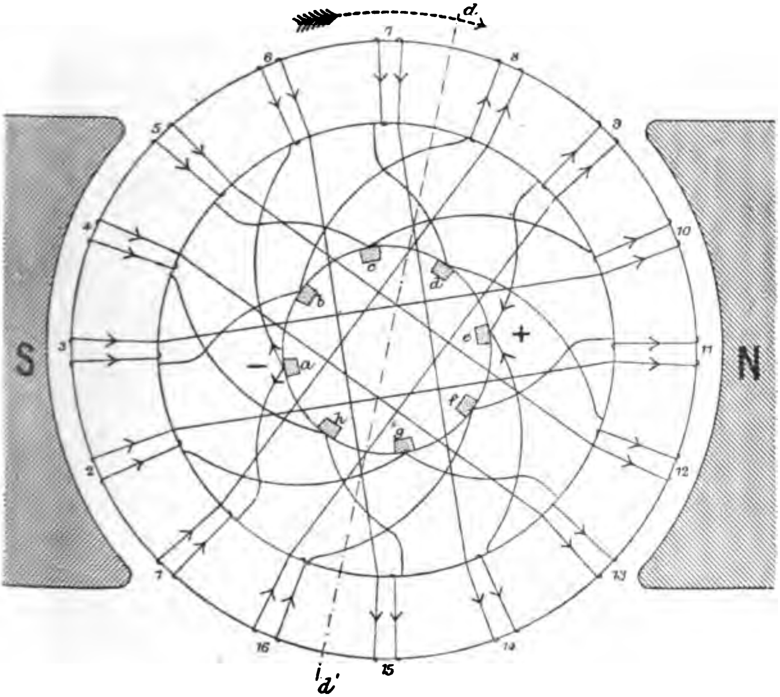
In the ring-winding Fig. 34, p. 40, $C = 32$; $p = 1$; $s = 8$; $c = 8$. Hence $y = 7$ or 9. But the ring ha sections only, of which, therefore, the seventh and the reckoned from any given section, are those that lie o side of it.

In the drum-winding, Fig. 70, p. 90, $C = 32$;

$b = 2$ (because each "element" of the winding from bar to bar of the commutator contains two active conductors); $s = 16$; $c = 16$. Hence $y = 15$ or 17. The former number may be taken as referring to the front layer of connexions (No. 1 to No. 16), the latter to the layer below them (No. 2 to No. 19).

A further example is afforded by a special ring-winding used by Wodicka, Fig. 205, in which each section is joined in series with one on the side opposite to it, so that the number of commutator bars is half that of the sections. Here each "element" of the winding consists of two sections, each containing active conductors; hence $b = 4$; $C = 32$; $s = 16$; $p = 1$; whence y may be either 9 or 7.

FIG. 205.

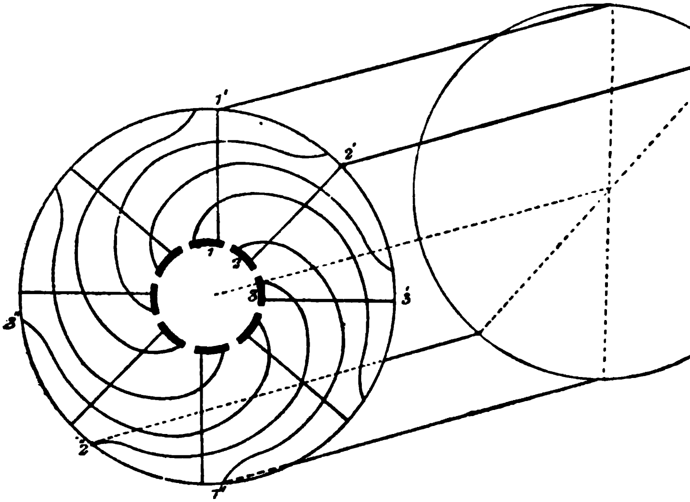


RING-WINDING WITH OPPOSITE COILS IN SERIES.

DRUM-WINDINGS.

In Fig. 206 is given a drawing of drum-winding appl
an 8-part armature. As in all Siemens' earlier drum
windings lay in two layers, each section being woun
metrically. Thus starting from the bar of the comm
marked 1 we pass outwards to 1′, then down the arm

FIG. 206.



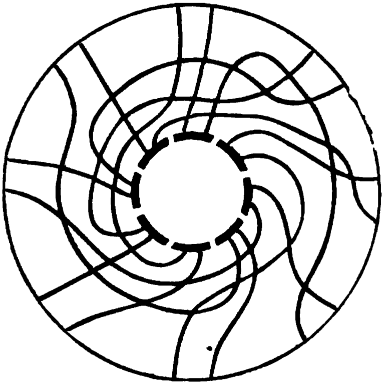
CONNEXIONS OF SIEMENS (VON HEFNER ALTENECK) WINDIN

across the back, up to 1″, and (after having wound a su
number of turns to form a section) spiral up to bar 2
commutator. In the original specification of Si
patent the end connexions were unsymmetrical, as sh
Fig. 207. The Edison variety of Siemens' winding is
in Fig. 208. The diagram only shows a simple case
7-part commutator. Here C = 14; $b = 2$; and accor
the formula y should be 6. But the actual value
spacing is 7 at the back and 5 at the front end, as
seen. With an odd number of sections commutatio

not occur simultaneously (in 2-pole machines) at both the brushes, but alternately.

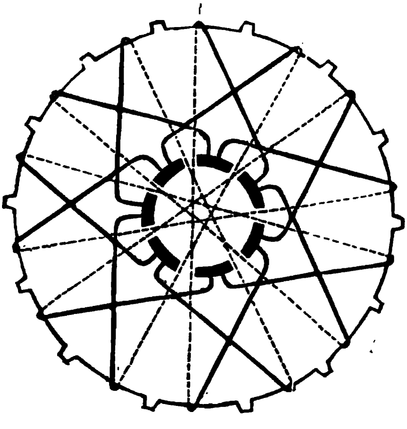
A closer study of the drum-winding is important, and accordingly there are given a series of winding diagrams relating to several varieties.

FIG. 207.



CONNEXIONS OF SIEMENS WINDING (OLD).

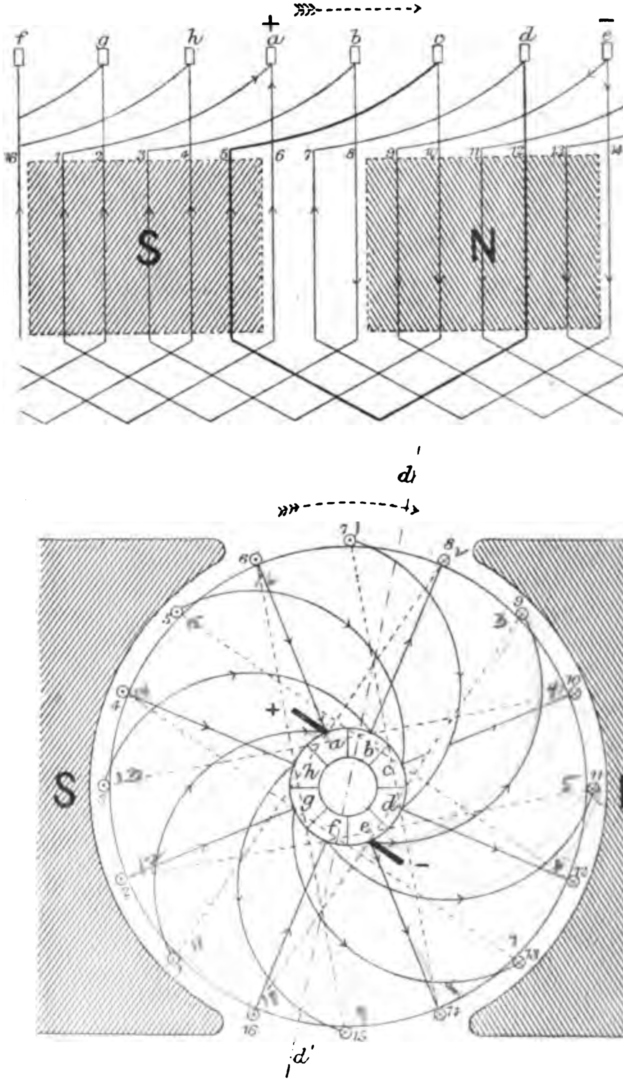
FIG. 208.



CONNEXIONS OF EDISON WINDING.

In Figs. 209 and 210 are given a right-handed wi
Siemens' plan for an 8-part commutator, and one

FIGS. 209 and 210.



LAP-WINDING (SIEMENS' RIGHT-HANDED) DEVELOPMENT AND E each section, *i.e.* with 16 conductors spaced round the periphery. The connecting pieces at the front end consist of straight connectors (such as *a* 6) and spiral connectors (such as *a* 1), which cross (either under or over) the former. The connecting pieces at the back end are not further indicated than by the dotted lines drawn across. In the developed diagram it is shown that each element of the winding is similar to *c*–5–12–*d*, and that the arrangement is a lap-winding. The back connectors space over seven conductors, being just short by one of the number $\frac{C}{2}$ in the semi-circumference; whilst the front connectors space over five, being short by three of the semi-circumference. It will be further noted that with this right-handed winding, rotating right-handedly in a right-handed field, the + brush is near the top of the commutator.

Figs. 211 and 212 represent the same thing, except that the winding is left-handed, with the result that the + brush is now near the bottom of the commutator.

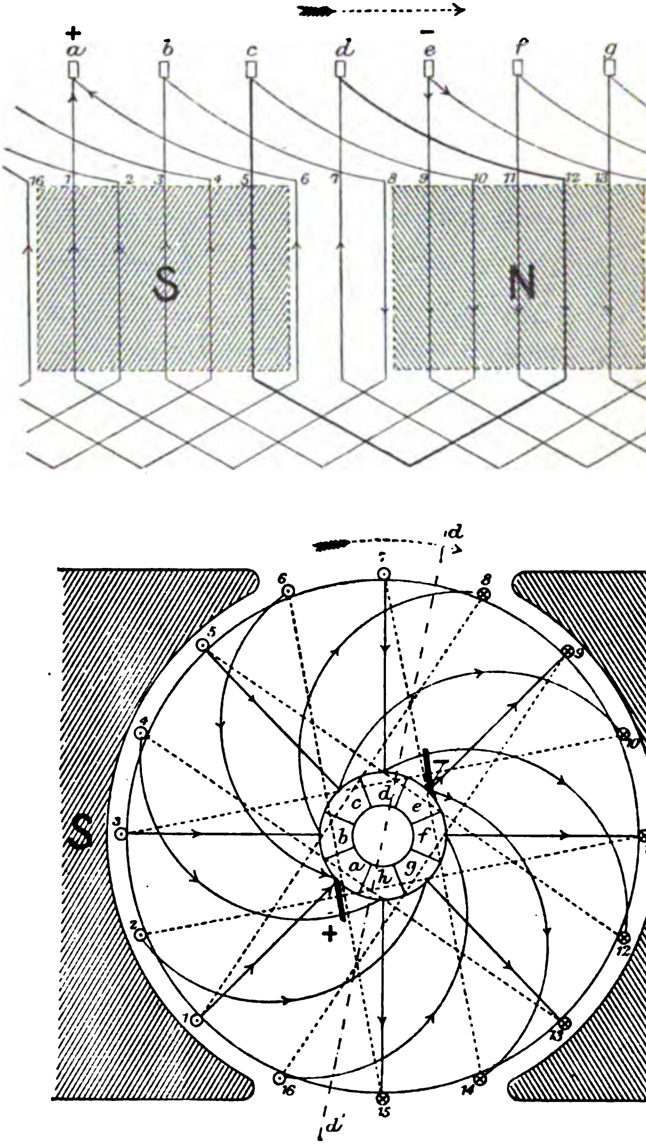
The winding table for both these Figures is the same, namely :—

F	B		F
+ *a*	1	8	*b*
b	3	10	*c*
c	5	12	*d*
d	7	14	*e*
− *e*	9	16	*f*
f	11	2	*g*
g	13	4	*h*
h	15	6	*a*

But in the right-handed winding the spiral connectors, such as *a* to 1, go toward the left, and in the left-handed winding to the right.

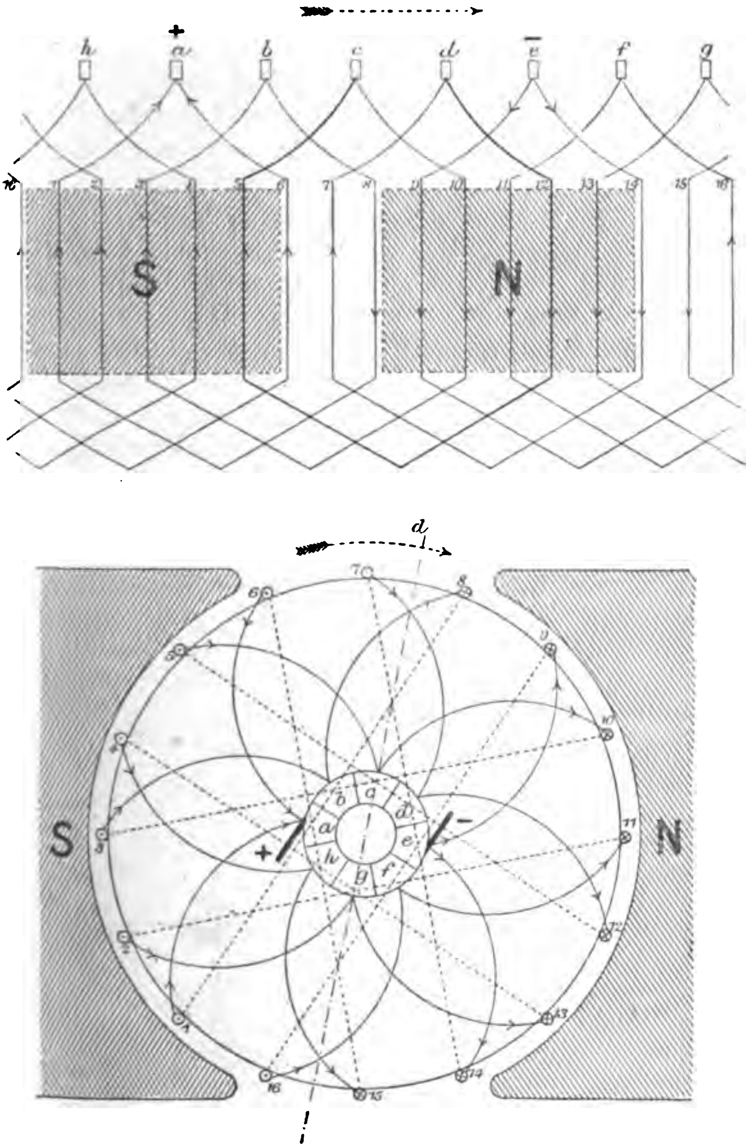
In Fig. 209 and Fig. 211 (the developments) it is seen that for both these windings the "element" of the winding,

FIGS. 211 and 212.



LAP-WINDING (SIEMENS' LEFT-HANDED) DEVELOPMENT AND
VIEW.

FIGS. 213 and 214.



LAP-WINDING (2-POLE SYMMETRICAL) DEVELOPMENT AND END VIEW.

indicated by the darker lines, is unsymmetrical at t
end of the drum, this being due to the use of two
front connectors, one straight, one spiral. The bar
commutator is connected to the front ends of co
No. 1 and No. 6. In one case it is skewed forwa
opposite No. 6; in the other it is skewed backwa
opposite No. 1. Why should it not be placed symm
between them?

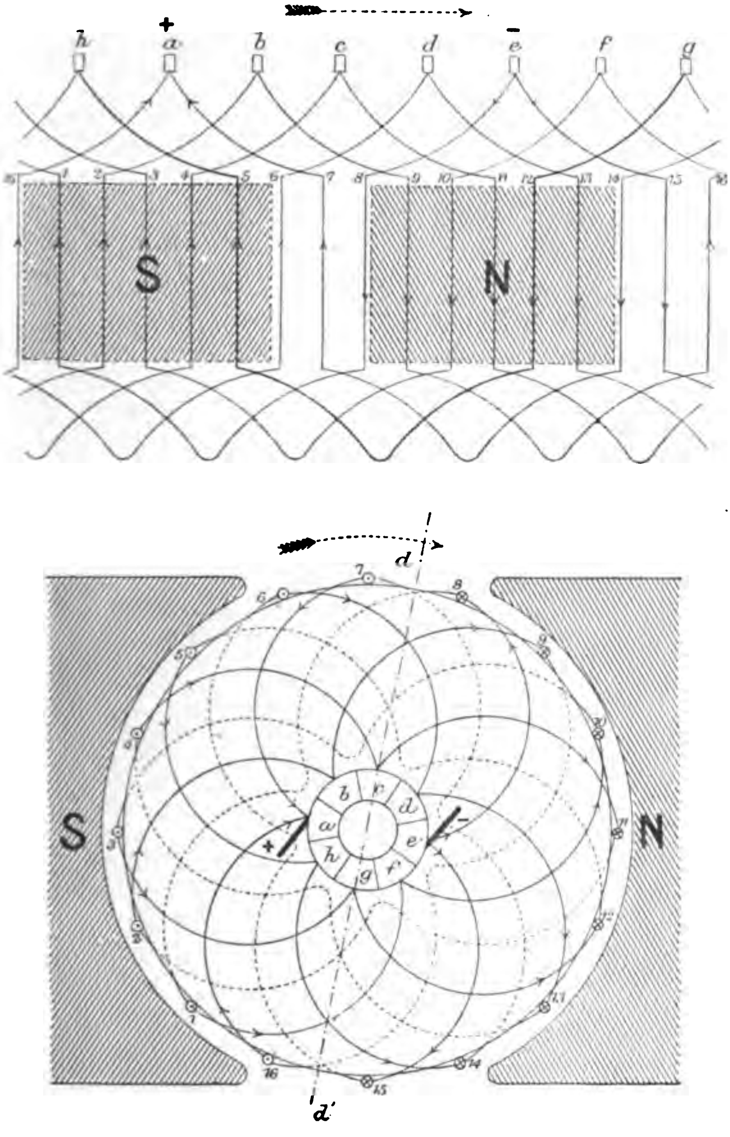
Figs. 213 and 214 depict a symmetrical lap-windi
trically precisely equivalent to the preceding, and ha
same winding table. The advantages are twofold:
built-up armatures) the connectors at the front end
all of the same pattern, consisting of two sets of shor
and that the brushes now come to a horizontal diamet
they are more accessible. The back connexions
exactly as before, and go across a longer chord than
connexions.

To secure the utmost symmetry in the winding,
and front connectors ought to be equalized. The the
proper spacing is $y = 7$ or $y = 9$. To attain this, j
to No. 8 at one end of the drum and to No. 10 at t
The result is shown in Figs. 215 and 216, from whic
once apparent that we have passed from lap-windi
wave-winding; each element passing around the d
returning only to the next bar of the commutator fro
it started. The winding-table for this case is:—

F	B		F
+ *a*	16	9	*b*
b	2	11	*c*
c	4	13	*d*
d	6	15	*e*
− *e*	8	1	*f*
f	10	3	*g*
g	12	5	*h*
h	14	7	*a*

Electrically, this winding is the precise equival

FIGS. 215 and 216.

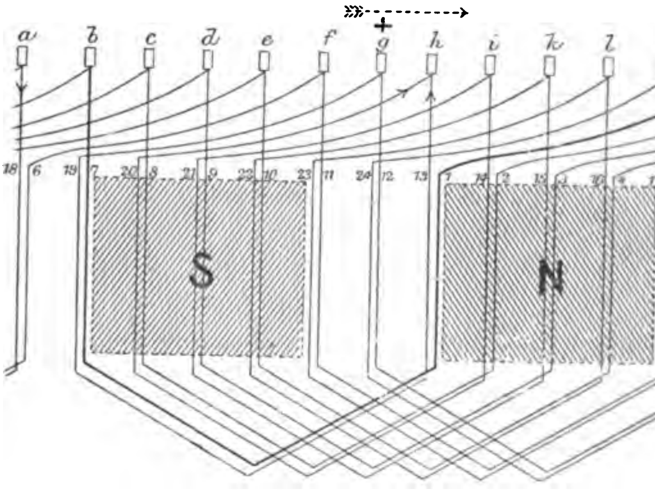


WAVE-WINDING (2-POLE SYMMETRICAL) DEVELOPMENT AND END VIEW.

three preceding. The spiral connectors at the back en in pairs as those at the front meet at the commutator.

A two-layer winding for twenty-four conductors, t with its development, are given in Figs. 217 and 218, s

FIG. 217.



TWO LAYER DRUM-WINDING.

how, when half the armature, from *a* to *g*, has been con one layer has been wound.

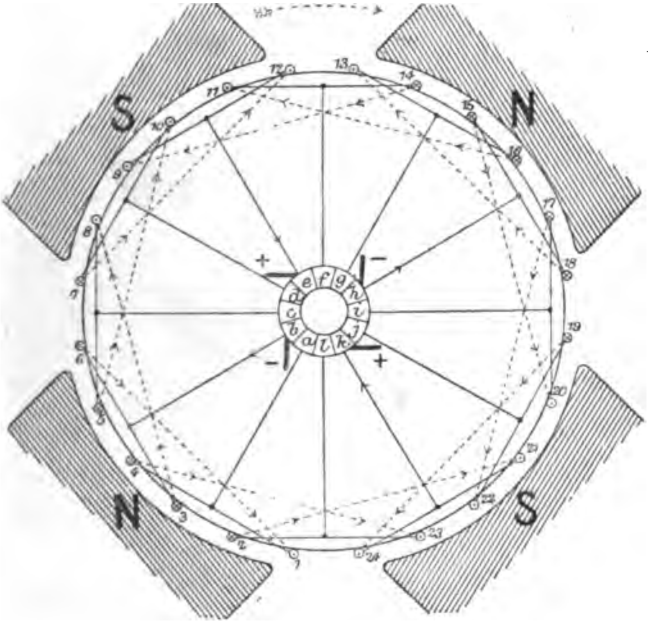
Multipolar Drums.—As mentioned on p. 337 bel winding of multipolar armatures with series-groupi suggested by Professor Perry.[1] It has been applied to winding by Messrs. Paris and Scott,[2] and by Mr. Kap the case of multipolar machines it is convenient to st rule in words that if a series grouping (so as to gi voltage) is desired, y must be an odd number and t

[1] Specification of Patent, No. 3036 of 1882.

[2] Specification of Patent, No. 4683 of 1884.

potentials from overlapping, and it can be well insulated because the separate sections can be wound on formers before being laid over the core.

FIG. 222.



THURY'S ARMATURE (4-POLE LAP-WINDING).

In Figs. 223 and 224 are shown two more complex windings due to Alioth.[1] In Fig. 223, which relates to a parallel grouping, the current entering at the negative brush bifurcates twice, finding four paths through the windings, two of the coils being short-circuited alternately at the + and − brushes. In Fig. 224 the connexions are rearranged so as to give only one bifurcation, and therefore only two rows of windings.

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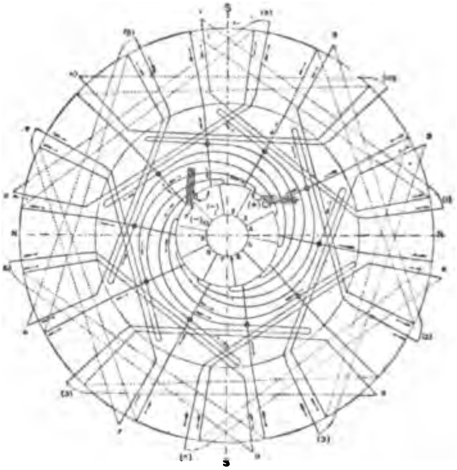
[1] See *Electrician*, xxiv. 140, Dec. 13, 1889, article by A. T. Snell.

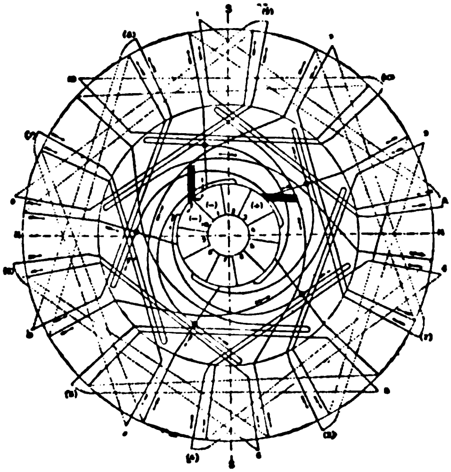
A method of drum-winding was proposed by Fritsc
which the conductors all lie obliquely across the surface

FIG. 223.



ALIOTH'S 4-POLE WINDING. PARALLEL GROUPING IN FOUR RO

FIG. 224.

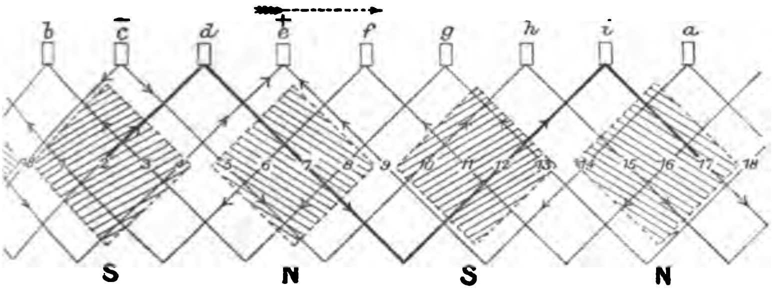


ALIOTH'S 4-POLE WINDING. SERIES GROUPING IN TWO ROW

Op. Citat.

drum, no part of them being parallel to the shaft. In this case the field-magnet poles are also constructed with diagonal faces. This oblique winding is shown developed in Fig. 225;

FIG. 225.



FRITSCHE'S OBLIQUE WAVE-WINDING.

which should be compared with the winding of Fig. 201, to which it is electrically equivalent.

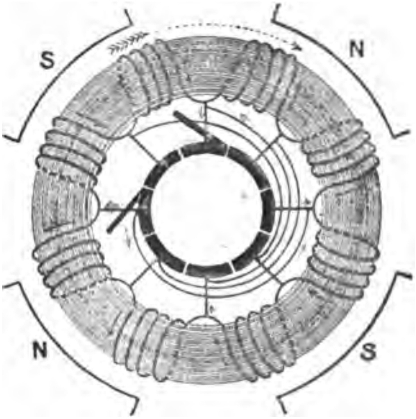
Multipolar drum-windings have also been proposed by Hopkinson and by Bradley.

MULTIPOLAR RING WINDINGS.

Of these something has been already said on p. 310. It was noted that an ordinary ring placed in a multipolar field would have as many neutral-points on its commutator as there are poles around it, and would therefore need as many brushes as the machine had poles. It is, however, possible to reduce the number of brushes to two, by two independent methods, one of which connects the rows of sections in parallel with multiple paths throughout the ring, the other puts them in series with but two paths through the ring.

In Fig. 226 is represented a mode of reducing the number of brushes to two, by cross-connecting windings at opposite sides of the ring, a device due to Mr. Mordey. This may be looked upon as simply putting into parallel with one another each coil and the one that occupies the similar place opposite the corresponding pole. The arrang looks unsymmetrical, but is not really so. For a machine each coil would need to be connected with th others at 120° on either side of it. There are several ways of doing this. One is by means of spiral conne another is by connecting across the corresponding b

FIG. 226.

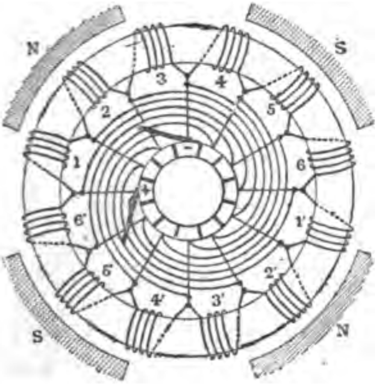


MORDEY'S METHOD OF MULTIPOLAR CONNEXIONS OF RING (PARALLEL CONNEXIONS).

the commutator. In the Victoria dynamos of the Company (p. 479) the length of shaft between the rin the commutator permits of double cross-connexion, junction of two adjacent sections being connected by down to the nearest bar of the commutator, and als nected round to that on the opposite side, as in Fig. 22 some of the Gülcher Company's dynamos the cross-conn is effected by a series of metal rings threaded on an ins sleeve over the shaft, each such ring having two diam lugs which cross-connect the wires leading down to op bars of the commutator. Such cross-connected ma really have four neutral points, but the brushes colle current from two only.

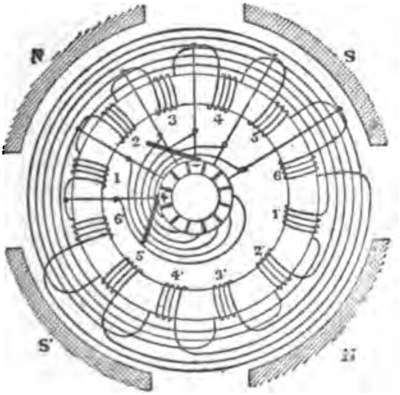
There are several methods of grouping the windings in series so as to gain a double electromotive-force. One of these modes, electrically symmetrical, is depicted in Fig. 228, wherein, while opposite coils are coupled in series, the commutator bars are cross-connected. This requires also but two brushes, at 90° apart. Two other modes of accomplishing the

FIG. 227.



CONNEXIONS OF VICTORIA (MORDEY) 4-POLE ARMATURES.

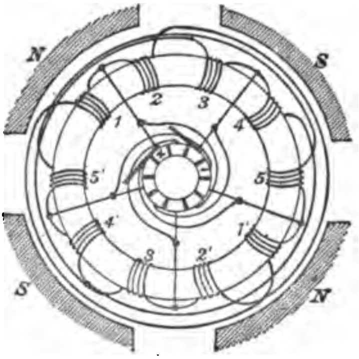
FIG. 228.



4-POLE RING, SERIES GROUPING (2 ROWS).

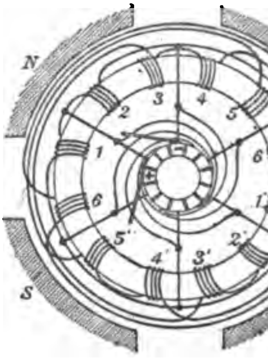
same end are shown in the windings of Figs. 229 a
Here, however, the connexions are not symmetrical,

FIG. 229.



4-POLE RING, SERIES GROUPING (2 ROWS).

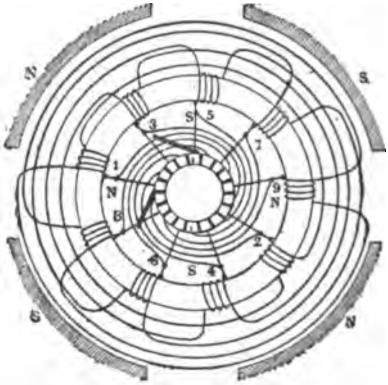
FIG. 230.



4-POLE RING, SERIES GR
2 (ROWS).

the resistances of the two paths (and therefore the res
currents) cannot be at all instants equal.

FIG. 231.



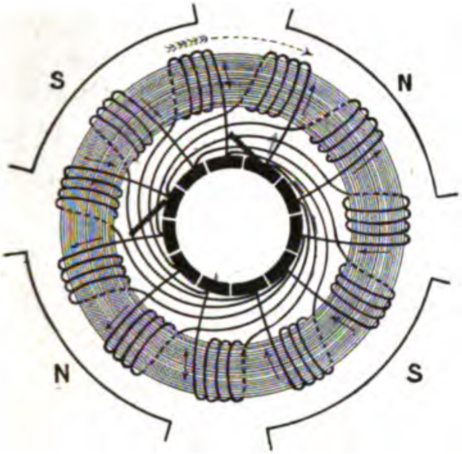
MULTIPOLAR RING.

In yet another arrangement (Fig. 231), each coil
nected down to p segments at intervals of $\frac{360^\circ}{p}$ aro

ring; and introduces an increased number of bars of the commutator.

Another winding, devised by Professor Perry, brings down the connexions from each section across a chord of the commutator. The case shown is that of a ring with eleven sections

FIG. 232.



PERRY'S METHOD OF MULTIPOLAR SERIES-GROUPING.

in a 4-pole field. The number of sections and of parts of the commutator must be odd if the number of pairs of poles is even. It may be either odd or even for 6-pole or 10-pole machines. Arnold points out that it is given by the formula:

$$S = p\,y \pm 1.$$

Arnold[1] has described numerous other ring windings of complex kinds.

DISK WINDINGS.

These may in general be treated as drum windings extended radially, the outer periphery corresponding to the back end of the drum. The earliest such winding is that

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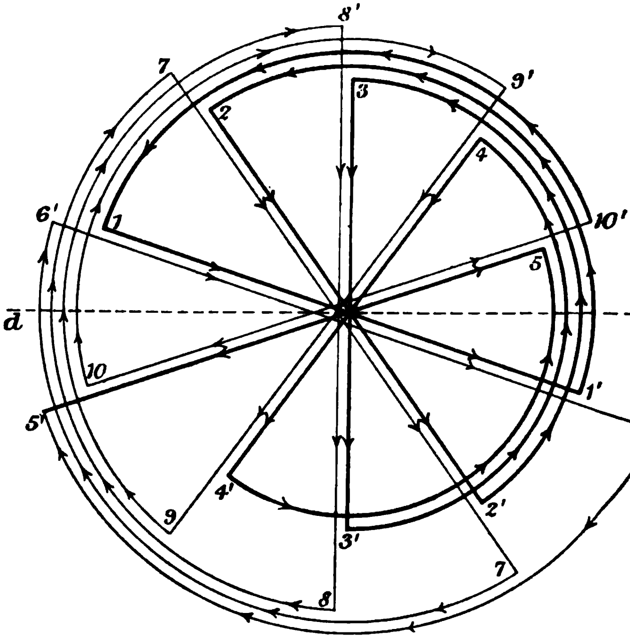
[1] *Op. citat.*

suggested in 1875, by Pacinotti. This is a lap-
adapted for a 2-pole field, the N pole being behi
upper part, the S pole behind the lower part in the c
will be noted that the outer end of each radial cond
carried round by a peripheral connecting piece to join
of another radial conductor, which for a 2-pole n
would be the one lying next but one to that which
metrically opposite. The schematic figure relates to a
armature, made up of twenty radial conductors. They a
bered so that the order of connexions may be trace
diameter of commutation being *d d*, the currents flow
inwards in one half and radially outwards in the other

FIG. 233.

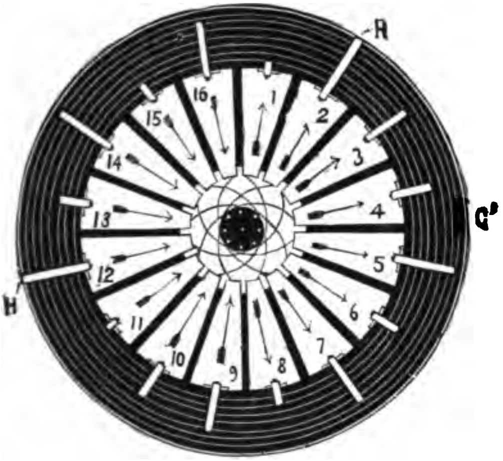


PACINOTTI'S DISK ARMATURE.

this disk. The construction of Pacinotti's exper
machines is described in his original paper.

Since then many suggestions have been made for windings of this description, including the one by Edison depicted in Fig. 234.

FIG. 234.



ARMATURE OF EDISON DISK DYNAMO.

In this disk the radial plate of copper, No. 1, is connected to No. 11 by straps of copper that meet an external insulated copper rim. The spacing here is over five and eleven conductors at the same time.

A lap-winding, identical with Pacinotti's, but adapted to a 4-pole field, is depicted in Fig. 235; it is known as the Edison "new disk" winding. The disk-armatures of Hookham's electricity meters are also lap-wound. Bollman devised a multipolar disk with a wave-winding.

Recently disk-armatures have been revived by Desroziers and Fritsche. Desroziers employs for a 6-pole machine the elaborate wave-winding shown in Fig. 236. A special study of this class of winding has been made by Arnoux.[1] Fritsche employs polygonal poles, enabling him to use, as conductors, strips of metal built up in star-polygon fashion without any

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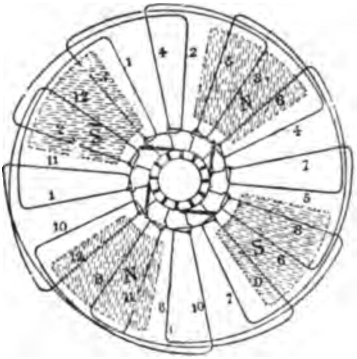
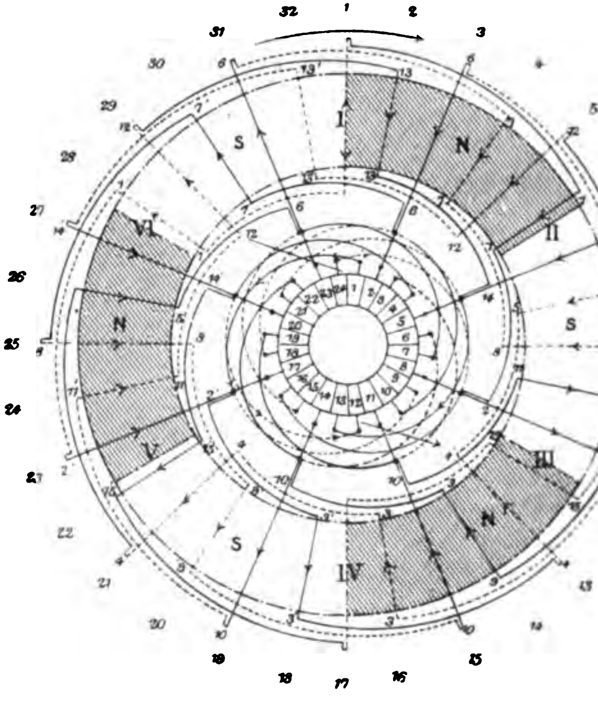
[1] See reference, p. 302.

FIG. 235.



4-POLE DISK LAP-WINDING.

FIG. 236.



DESROZIERS' 6-POLE DISK WINDING.

radial parts—a structural advantage. His disk, if developed out straight would, for a 4-pole machine, be adequately represented by Fig. 225, p. 333. The two sets of conductors constitute two layers which are united at their outer ends to the bars of a commutator at the outer periphery. The disk armature of a Fritsche machine, removed from the magnets, is shown in Fig. 36, p. 44.

CHAPTER XIII.

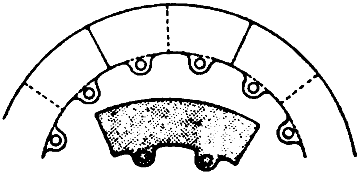
PRACTICAL CONSTRUCTION OF ARMATURES.

TO carry out the proper magnetic, electric, and me conditions of armature construction needs electrical kn mechanical training, and experience. The mechanical p involved have been set forth in Chapter V.; the n problems in Chapter VII.; and the theory of armature- has been discussed in Chapter XII. In those chapte is, however, little said about the proper modes of secu armature-conductors, of insulating them, and of ve them. Most, though by no means the whole, of the chapter relates to the armatures of direct-current and motors; but much of it is equally applicable to a current machines.

ARMATURE CORES.—Cores are always laminate constructed either of (1) sheet iron *disks*, (2) iron (3) iron *wire*. Ribbon is only used for discoidal a magnetized through the flanks. For drums and e rings, disks stamped out from soft sheet iron ar universal. The usual thickness is from 1 to 2 n from 40 to 80 mils). They should be of the soft showing the least possible hysteresis. After being out they should be annealed, and the burr at the moved. Some makers at this stage assemble them shaft, turn them down truly in the lathe, then ta apart and remove the burr by grinding lightly on a wheel, then re-mount them. Before being finally on the shaft they must be lightly insulated one other. For this purpose it is usual either to cover of each core-disk with varnished paper, or to ena faces of each core-disk. Mica insulation here woul expensive, and is not necessary, as only a moderate insulation is requisite. It is usual to make the two end core-disks of stronger iron, sometimes as much as 6 mm. or ¼-inch thick. For discoidal armatures the iron ribbon must be insulated with an interposed band of varnished paper. To stiffen a discoidal armature-core it is usual to build it upon a foundation ring of soft iron, and this in some cases is constructed with a projecting central iron web, on either side of which iron ribbon is coiled. An example is afforded by the core of the Victoria (Mordey) machine, Fig. 335, p. 498.

For large machines the expense of the core-disks becomes disproportionately great owing to the waste in stamping. Hence various suggestions have been made to use segmental portions. For many years the cores of Joel's "engine-dynamos" have been built of pieces bolted together, in order to permit of the ring-windings being separately wound and slipped on. In Kapp's multipolar drum armatures (Plate IX., Fig. 2), the cores are segmental, being constructed, as shown in Fig. 237, of pieces which overlap in successive layers, each piece having eye-holes for bolts.

FIG. 237.



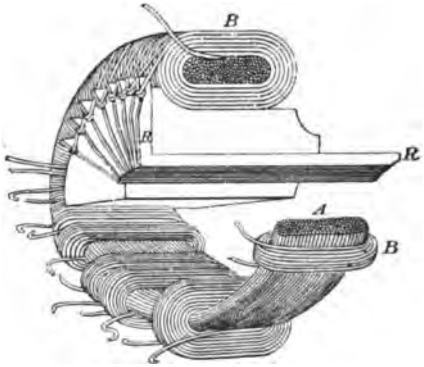
SEGMENTAL CORE-DISKS (KAPP).

Wire cores were at one time largely in vogue, having been used by Gramme. The soft iron wire, varnished or slightly oxidized on its surface, was wound on a special former, then removed, taped externally, and wound with the copper wire conductors.

Wire cores have three disadvantages. (i.) they are mechanically less satisfactory than disk cores ; (ii.) they fill a given core-space with an actually less nett cross-section of iron, owing to the interstices between the separate wires, only about three-fourths of the total cross-section being occupied by iron ; and (iii.) they present a discontinuity radially which offers an unnecessary reluctance in the path of the magnetic lines.

The substitution of a square iron wire for a round on
the core of the Gülcher Company's dynamos (Fig. 339,
is an improvement in all these respects.

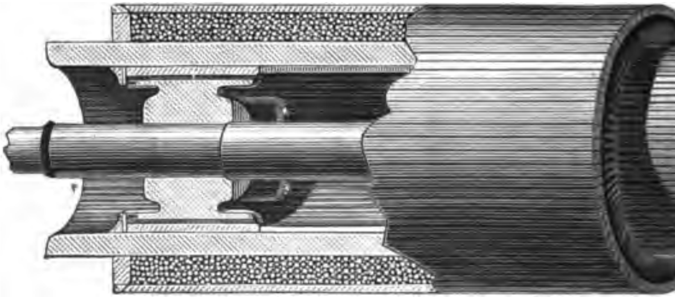
FIG. 238.



GRAMME RING WITH WIRE CORE (1871).

For machines of large output, Gramme designed the a
shown in Fig. 239. It consisted of a hollow cylinder, buil
100 wedge-shaped copper bars, each covered with a bitu

FIG. 239.



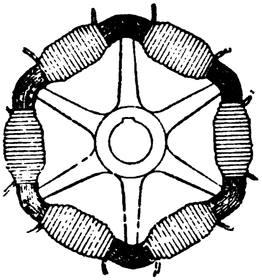
GRAMME ARMATURE FOR LARGE CURRENTS (1882).

paper wrapping, and then put together. Each bar had tw
projections of copper. The protruding ends of the copp
formed the commutators, of which there were two. Th
between the two sets of radial projections was filled with v

of varnished iron wire which constituted the core, and finally 100 other bars of copper of flatter section wire connected exteriorly from the projecting lug at one end of one bar to the lug at the other end of the next bar, so connecting the bars into a closed coil. Several of the inner bars were made thicker and of special form, so that they might be keyed to spiders fixed upon the driving-shaft.

Another mode of constructing wire cores is presented in the Bürgin machine. The armature of the original machine, as it came from Switzerland, consisted of several rings set side by side on one spindle, these rings being made of iron wire wound upon a square frame, and carrying each four coils. Mr. Crompton changed the square form to a hexagon having six coils upon it (Fig. 240), and increased the number of rings to ten. It was thus described in 1882:—"Each ring is made of a hexagonal coil of iron wire, mounted upon light metal spokes, which meet the corners of the hexagon. Over this hexagonal frame, six coils of covered copper wire are wound, being thickest at the six points intermediate between the spokes, thus making up the form of each ring to nearly a circle. Each of the six coils is separated from its neighbour, and each of the ten rings is fixed to the axis one-sixtieth of the circumference in advance of its neighbour, so that the sixty separate coils are in fact arranged equidistantly (and symmetrically as viewed from the end) around the axis. There is a 60-part collector, each bar of which is connected to the end of one coil and to the beginning of the coil that is one-sixtieth in advance; that is, to the corresponding coil of the next ring. This armature has the great practical advantages of being easy in construction, light, and with plenty of ventilation."

FIG. 240.

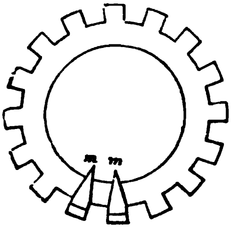


SINGLE RING FROM CROMPTON-BÜRGIN ARMATURE.

This form, however, suffered from the harmful effects of induction between contiguous rings, and it was found advisable to alternate the positions of the rings, instead of placing them in a regular screw-order on the spindle, as shown in most of the published drawings of this once well-known machine. It proved to be in no way superior to an ordinary Gramme armature, provided the latter was of good mechanical construction and with a sufficient cross-section of iron in the core.

Toothed and Smooth Cores.—Pacinotti's armature c (Fig. 241), was a toothed ring of solid iron supported o spokes, and having boxwood distance pieces fixed to th to hold the windings apart. Armatures built up of t core-disks have been much used in recent years, parti for motors. They have two advantages over smooth arm (i.) The teeth present an excellent means of driving the conductors which lie between them ; (ii.) the teeth n brought very close to the polar surfaces of the field-n with very narrow clearance, bettering the magnetic circu therefore reducing the amo copper required to excite the m flux. To set against thes advantages are the disadvanta somewhat greater labour requi milling out the channels betw teeth of the assembled core ; th difficulty of insulating the cor the conductors ; and the liabi the teeth to set up eddy-c (see p. 99) in the polar faces latter can be cured by making the teeth numero narrow, also by laminating the polar faces with groov by enlarging the clearance. Or, best of all, by finally the entire armature outside the copper conductors layer of iron wire. The magnetic gain in using iro between the conductors is so great that sundry const notably Messrs. Chamberlain & Hookham, and Lahmeyer & Co., have built up iron projections smooth core-disks.

FIG. 241.

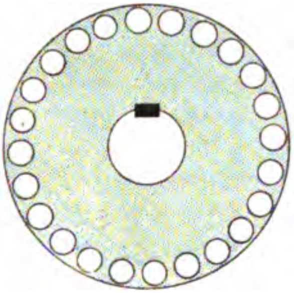


PACINOTTI'S TOOTHED-RING ARMATURE.

Examples of discoidal cores having toothed project the flanks are afforded by the Brush armatures, Figs. 3 303, p. 462.

Pierced Core-disks.—The advantages offered by t core-disks are possessed to a still higher degree by cor pierced with apertures just within the periphery. Suc been used by Wenström, by Swinburne, and by Brown. In such armatures the conductors are carried in tubes of insulating material that pass through the perforations. Brown has found this construction eminently satisfactory from the mechanical and magnetic point of view. It is used both in his drum-armature and ring-armature machines, Plates IV. and X., and Plate XXVII., Fig. 1, constructed at the Oerlikon Works. It is not however, suitable for high voltages, exceeding 100 volts or so, owing to the difficulties of insulation. One peculiar and valuable property of the pierced core-disks is, that they completely protect the embedded copper conductors, however massive, from parasitical eddy-currents which would otherwise be generated in them.

FIG. 242.



PIERCED CORE-DISK.

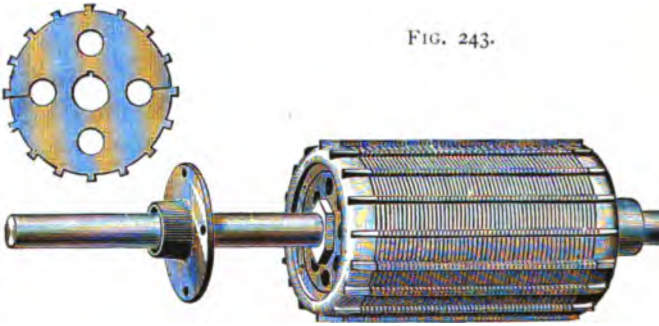
Driving Spokes and Spiders.—Armature cores are usually built up upon an internal frame or skeleton pulley firmly keyed to the shaft. In drum armatures this internal supporting frame may be omitted, the core-disks themselves being keyed directly on to the shaft. Messrs. Laurence & Scott punch hexagonal holes in the core-disks and thread them on over a hexagonal shaft.

In Weston's drum-armatures the core-disks, perforated for ventilation, are keyed to the shaft, as shown in Fig. 243.

Frequently the core-disks are held together by insulated bolts passing through them, and driven by spiders keyed to the shaft, as in Fig. 244. To this construction there is the objection that the bolt-holes reduce the effective cross-section of iron and strangle the magnetic flux. It is also needful that the bolts should be insulated from the arms of the spiders by ebonite washers and bushes, otherwise the framework will constitute a closed circuit for eddy-currents which will heat it.

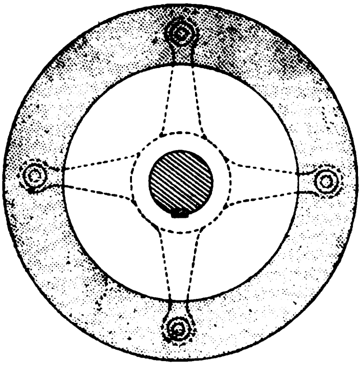
A better mode is that used by Messrs. Paterson & in their Phœnix dynamos (Fig. 331, p. 492, and Pla in which the section of the iron is but slightly reduced a bolts are entirely internal to the core. The dimensions machine are seen in Plate V., Fig. 2.

FIG. 243.



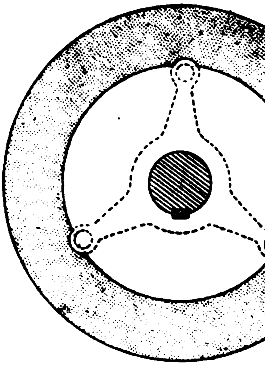
WESTON'S ARMATURE CORE AND CORE-DISK.

FIG. 244.



MODE OF DRIVING CORE-DISKS.

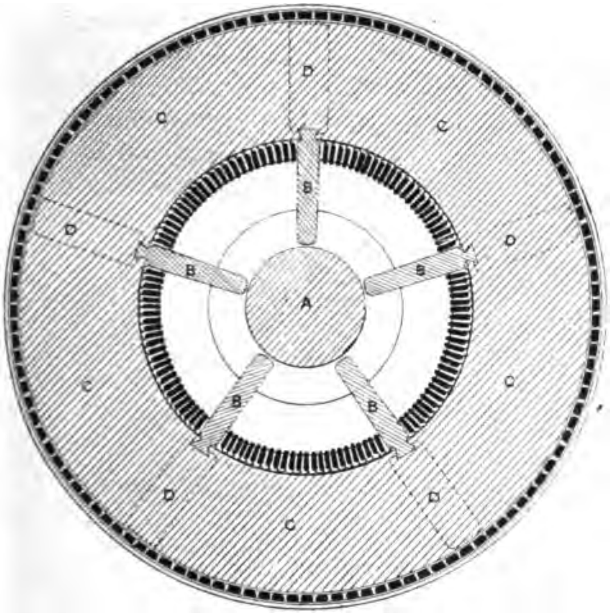
FIG. 245.



PATERSON AND COOPER'S M
OF DRIVING CORE-DISK

Another mode is to provide the core-disks with d notches into which pass long flanges from the shaft Crompton, in 1886, introduced this construction in th illustrated in Fig. 246. The coils are wound upon an iron core made up of disks of very thin soft iron fixed upon a central spindle by means of short arms, which are dovetailed into notches cut in the inner circumference of the disks. At intervals gaps are left between the disks, for ventilation. The coils, ninety-six in number in some of these machines, one hundred and twenty in others, are threaded through the cylinder, and kept in their places by small boxwood wedges and by external bindings of thin brass wire. This armature is 2 feet 4 inches in length, and $12\frac{3}{4}$ inches in external diameter. The steel shaft A is grooved with five deep slits to receive five flange-like spokes B, which dovetail into notches in the iron disks C. At every 2 inches of the length there are inserted the pieces D, which are $\frac{1}{8}$ inch thick, to preserve

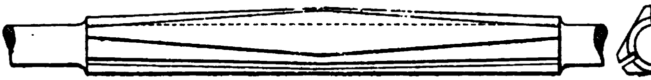
FIG. 246.



SECTION OF CROMPTON ARMATURE (1886), SHOWING DRIVING FLANGES, DOVETAILED INTO NOTCHES IN CORE-DISKS.

ventilating gaps. Mr. Crompton's method of connecti
the driving shaft by grooves in the latter, is also sh
Fig. 247, which illustrates a shaft with three grooves.

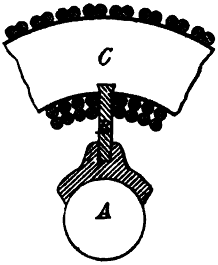
FIG. 247.



DRIVING SHAFT OF A CROMPTON DYNAMO.

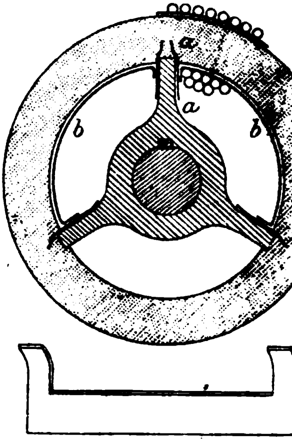
Owing to the cost of manufacture, these grooved
are now seldom used; a ribbed sleeve, which slips o
cylindrical shaft and is driven by a long feather, is less
and equally mechanical. Fig. 248 illustrates a form
such a sleeve; and adapted for receiving a wire-win
one layer externally and two layers internally.
recently Mr. Crompton makes the four projecting fla
one solid structure instead of four separate pieces.

FIG. 248.



CROMPTON'S WIRE-WOUND ARMATURE.

FIG. 249.



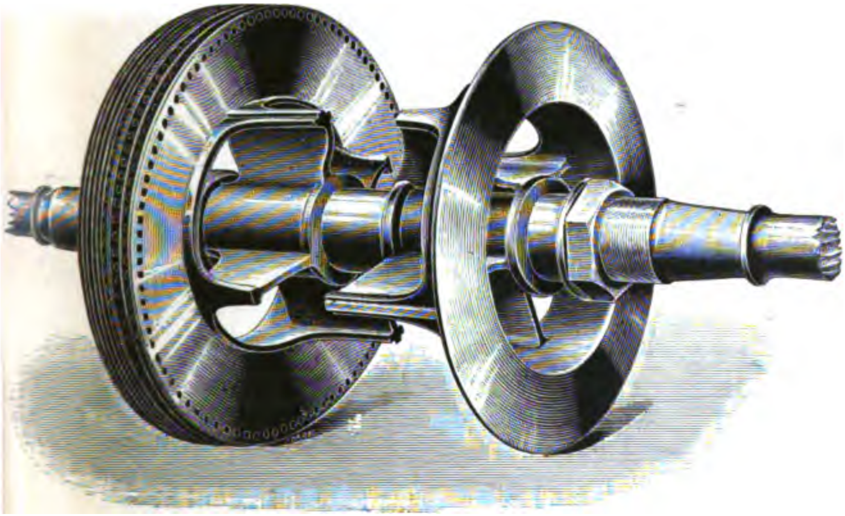
KAPP'S MODE OF DRIVING CORE-DISKS.

Kapp's mode of driving the core-disks is shown in Fi
which should be compared with Plates I. and II.

the shaft is slipped on a long sleeve provided with three projecting flanges to support the core-disks. This sleeve, which is prevented from turning by a long feather slightly sunk into a key-way, has the advantage of stiffening the shaft. In armatures for ring-winding, this internal structure is of gun-metal; in those for drum-winding, of cast iron. It is pushed up towards a face-plate which rests against a shoulder on the shaft, and the core-disks are tightened together between the two face-plates by a nut on the shaft.

Brown's mode of supporting and driving the core-disks is shown in Fig. 250.

FIG. 250.



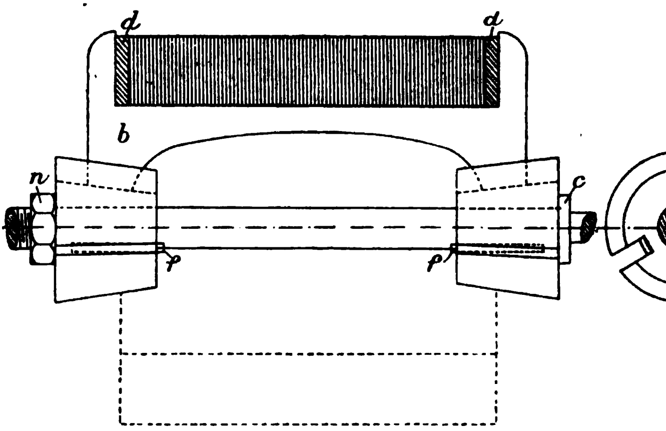
BROWN'S MODE OF DRIVING THE CORE-DISKS.

The spiders are two in number, each having four internal web-spokes and wide end-flanges. They fit over the shaft, with feathers to prevent turning. One of them is held up against a shoulder on the shaft; and after the core-disks have been assembled, the other one is pressed up by a large hexagonal nut. It will be noticed that two of the webs on

each spider are ribbed; the core-disks being stampe
notches to prevent them turning. Of the four web-
two are long and two short, so that the core-disk
be compressed as the spiders are forced together.
similar arrangements for holding up the core-disks e
Hopkinson's "Manchester" dynamos, and in Holmes's "
dynamos.

Another arrangement, admirable for its streng
employed in Immisch's motors and dynamos. Up
shaft are placed two gun-metal cones, with shallow f
to prevent turning. In each cone are cut three slots at

FIG. 251.



IMMISCH'S METHOD OF DRIVING BY TWO CONES.

of 120°, the bottoms of the slots also sloping cone-wise
these slots fit three bridge-like gun-metal flanges, wi
jecting lugs at their ends, to hold up the core-disk
screwing up a nut on the shaft the cones are pressed to
and thereby the three flange-spokes are forced outwa
support the core-disks at three points of their i
periphery. Coned devices resembling more or less this
mechanical arrangement, are to be found in some
of ring armatures designed by Spang, and in
designed by Raffard. In the case of the Immisch m

the core-disks are neither notched nor keyed; but at the ends, and at intervals, thicker iron disks are inserted with projecting driving horns.

It should not be forgotten that compressing stresses diminish the magnetic permeability of iron in the direction of the stress; and that tensile stresses increase the permeability.

Insulation of Iron Cores.—Mention has been made of the proper mode of insulating the core-disks internally from one another by interposing paper or enamel. Theoretically there is no need to insulate them from the shaft in those cases where they are threaded on directly; it is at their peripheries mainly that they must be prevented from making metallic contacts with one another. But beside this internal insulation, they must be protected very carefully from *external* contact with the copper conductors. It is usual to serve the completed core with one or two coats of enamel or japan, and then to cover it with a layer of some tough material such as canvas, manilla-paper, or Willesden-paper, well varnished with shellac varnish or with Scott's rubber varnish. In the case of cores for ring-winding, particular care must be taken to insulate the inner periphery and the driving spokes, where the internal windings lie near them. In the case of drum cores, the ends must be well protected, and those portions of the shaft that are close to the ends. In Kapp's ring armatures, pieces of thin vulcanized fibre, of the form shown in Fig. 249, p. 350, are inserted on each side of the driving flanges, and other pieces are coiled around the internal periphery between the flanges in the manner shown. The mode of insulating the cores of Brush rings is described on p. 455.

Ventilation of Armatures.—Armature cores heat from three causes: hysteresis; eddy currents; and heat derived from the copper conductors. The careful lamination and insulation described above, are but means to prevent waste of power and to avoid risk of overheating. In the case of ring-wound machines there is usually an amount of surface exposed sufficient to get rid of the heat generated in the conductors without resorting to any special mode of ventilating. But in the case of large and solidly constructed drum-armatures,

some mode of forcing the ventilation may be neces
drum-armatures with the old-fashioned wire-windin
lapping the ends, adequate ventilation is impossi
examples of ventilated cores the reader should see Cr
armature, Fig. 246, p. 349; Kapp's drum-armature,
Fig. 1.

In the case of drum-windings having end connex
up, the arrangements with one set of evolute spirals ar
of straight radial pieces (as in Fig. 212, p. 322) are p
to those with two sets of spirals as in Fig. 214, p.
the former have a better fan action. Some makers us
with arms sloped like the sails of a windmill, so as
air through the interior of the armature.

Balancing of Armatures.—It is very needful that a
should be properly balanced, otherwise they will s
jurious vibrations in running. Most makers test the
tures for balance by laying the journals on two paral
rails (or "knife-edges") and noting whether the arma
remain in any position without tending to roll. It is we
to balance them thus on completing the core ready for
and again after winding. If the end core-disks ha
made of thick iron, holes can be drilled in these t
perfect balance: or leaden plugs can be inserted.

It may be remarked that this mode of obser
statical balance is not perfect; for if the masses that
around the axis are distributed unsymmetrically a
axis, there will be, when running, a tendency to spin
the axis of maximum moment of inertia, which will
vibration.

Driving Horns.—It is of primary importance that t
ture conductors should be properly driven, otherwise t
be raked out of place by the tangential drag in the
field (p. 111). In the case of ring-windings, such
action is less likely to occur than with drum-winding
convolutions which thread through the interior of
tend to bind, and press against the driving spokes.
here, it is found needful to provide positive driving at a
of points around the periphery. Crompton found it n

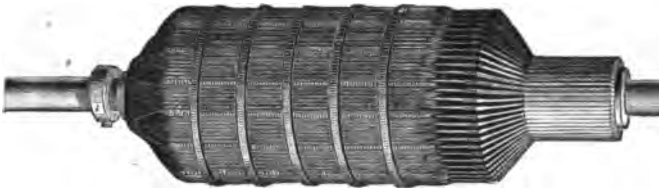
drive boxwood wedges in between the core-disks. He then adopted the construction of Fig. 246, p. 349, in which the pieces of fibre D are inserted at intervals for ventilation between the core-disks; the gaps so left being convenient for the insertion of driving horns between the wires. Kapp uses projecting narrow steel horns protected by pieces of hard fibre. Goolden uses strips of hard white fibre inserted into shallow keyways milled out of the surface of the core; there being usually 24 short fibre keys, inserted in 8 rows of 3 each, the rows being 45° apart. They are held in by the external binding wires. For discoidal armatures the driving horns must project at the flanks, being inserted between the core ribbons.

Binding Wires.—After an armature has been wound the conductors must be secured in their place by a number of external bands, known as *binding wires.* These must be very strong, to resist centrifugal force and to hold the conductors from being dragged aside; and yet at the same time must occupy very little radial depth, that the clearance between conductors and pole-face may be as narrow as possible. Some makers use hard-drawn brass, others phosphor-bronze, others steel, for binding wires. The almost invariable practice is to employ a tinned wire, which, after winding, can be sweated together with solder into a continuous band. It is impossible to give rules for the sizes of binding wires. A frequent size for steel wire is 40 mils, or a little under 1 mm. diameter. The wire is wound on in bands of from 10 to 30 turns each; the separate bands being spaced out at distances of from 1 to 2 inches apart. Under each belt of binding wires a band of insulation must be laid. This usually consists of two layers; first a strip of thin vulcanized fibre slightly wider than the band of wires, and then a strip of mica (in short pieces) of about equal width. Some makers lay a small strap of thin brass under each band of binding wires, having ends which can be turned over and soldered down to secure the two ends of the wire from flying out. Fig. 252 depicts a completed drum-armature of Weston's pattern (compare Fig. 243, p. 348) showing five bands of binding wires.

Mr. Esson states that Messrs. Paterson and Cooper use

three sizes of piano steel wire, namely 18 mils, 20 m
26 mils, respectively in diameter. On a drum arma
inches in diameter and 12 inches in length he would p

FIG. 252.



COMPLETED DRUM ARMATURE (WESTON'S PATTERN).

bands of 18-mil (*i.e.* No. 26 B.W.G.) wire, each ban
about $\frac{5}{8}$ inch wide and containing about thirty-three
the bands being, therefore, rather less than $1\frac{1}{2}$ inche
On a drum or ring 20 inches in diameter he would us
wire, in bands $\frac{1}{2}$ inch wide, about 2 inches apart.

Winding Armatures.—Given a scheme of winding
ing to any of the modes discussed in Chapter X
problem remains how to carry it out in the factory.
windings may be considered first, then drum-windings.
windings, as carried out by Desroziers and by Frits
sufficiently discussed on p. 337. A broad distinction
set up between wire-wound armatures and those with
coils consisting of bars and connectors, or of special
structed portions that are put together instead of bein
on. Wire-wound armatures are usual for output
100 amperes, including all arc-lighting machines. Fo
tures having outputs exceeding 200 amperes bar-ar
are more frequent, owing to the inflexible nature of wi
are thick enough to carry these currents. The two
comprise several varieties as under:—

WIRE-WOUND ARMATURES.

Single round wire.
Two or more round wires in parallel.
Stranded wire.
Single square wire.
Single rectangular wire.
Laminated strip conductor.

BAR ARMATURES.

Round bars.
Rectangular bars.
Imbricated rectangular str
Rectangular bars of compr
stranded wire.
Special forgings.

Single round wire, insulated with double cotton covering soaked afterwards with shellac varnish, is usually adopted for small machines and arc-lighting dynamos. Messrs. Goolden & Co. use silk-covered wire. For small electroplating dynamos it is frequent to use several round wires in parallel, even to as many as twenty or thirty separate wires side by side. Wire-drawers will furnish rectangular wire of any desired section; but, for greater flexibility in winding, a rectangular conductor made of three or four separate strips laid side by side, and then served with a coating of tape to hold them together is preferable, and has been for some years used in Holmes's dynamos. It has the advantage of partially eliminating eddy-currents in the conductors themselves.

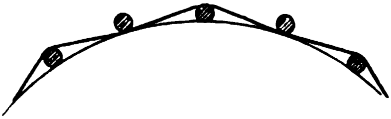
For bar-armatures rectangular bars set edge-ways to the core are more frequent than round bars; but armatures in which solid bars are used are liable to a serious waste of work that does not occur with wire-wound armatures. When the conductors present a considerable breadth, eddy-currents are set up in them as they enter or leave the magnetic field, owing to the fact that one edge of the bar may be passing through a field the intensity of which is very different from that of the field through which the other edge of the same bar is passing. Assuming a peripheral speed of 1700 to 1800 feet per second, it is found in practice impossible by any shaping of the pole corners to avoid excessive heating of solid copper bars on the armature if their breadth exceeds 5 mm. The work wasted in producing these eddy-currents may even reduce the efficiency of the dynamo by more than 5 per cent. This does not, however, occur in those armatures in which the bars are sunk deeply between teeth, or pass through holes in the core-disks. To reduce such losses, bars made of several strips oxidized on the surface, or lightly insulated by oiling or enamelling, and united only at their ends, have been used. Crompton[1] has proposed several modes of twisting or imbricating around one another two or more strips, so as more effectually to neutralize the eddy-currents. More recently he and other makers have used bars made of stranded copper wire compressed into a rectangular form, each wire being oxidized or lightly insulated.

---

[1] See *Journal Institution Electrical Engineers*, xix. 240, 1890.

Yet another mode of armature construction, described later, consists in winding the insulated wires or strips upon special formers or moulds, in groups which are afterwards laid on or around the armature core. One advantage in such methods is the greater ease of securing perfect insulation between those parts of the windings which differ greatly from one another in potential. In drum-windings, if the conductors lie in one layer, there is an extreme difference of potential between each conductor and its next neighbour. Whereas if they lie in two layers, an intermediate sheet of insulating material can be laid between. It has also been suggested that in one-layer windings an insulating sheet may be introduced, as in Fig 253, to keep the two sets of conductors apart.

Fig. 253.



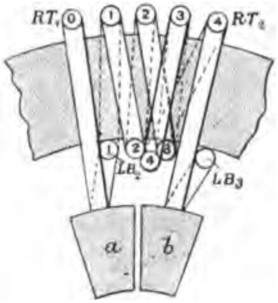
Insulation of Alternate Windings.

Wire-wound armatures are usually well served with shellac varnish or indiarubber solution after the winding is completed. They should be well dried in a stove at steam-heat after varnishing.

Modes of Winding Ring Cores.—When a ring core is to be wound it is frequent to stencil upon the end faces a number of radial lines corresponding in breadth to the separate sections so as to guide the winder in his work.

For ring-windings there is, in general, little trouble. Nevertheless some care must be exercised. The separate "sections" of the coil are almost invariably wound on the cores separately, leaving the ends projecting, secured temporarily with string, and these ends subsequently connected together and to the commutator. An inexperienced workman may easily connect up wrongly; making a left-handed winding instead of a right-handed one, or *vice versâ*. Hence it is well to provide him with some such working drawing as Fig. 254, which relates to a right-handed winding having four turns in each section. The wire marked "0" is the last or outer end of the section previous to that considered. This end will eventually be brought down to a bar *a* of the commutator, and from this bar will go out the beginning or left-bottom end, marked L B, of the section in question. Looking at this diagram the winder will see that the wire L B must pass under the core to the far end and then return over the top, thus making turn No. 1. It will then bend down to the right, be threaded through again, and make turn No. 2; again, and make turn No. 3; but as the inner space is narrower than the outer space, turn No. 4 will probably have to ride on, or partly bed between, the turns already wound. The right-top end, marked R T, will eventually be joined to bar *b* of the commutator. If the winder is shown that the right-top wire of one section joins the left-bottom turn of the next section at the commutator, he will have no excuse for mistakes. The winding of multipolar rings is absolutely similar, provided as many brushes are applied to the commutator as there are poles.

FIG. 254.

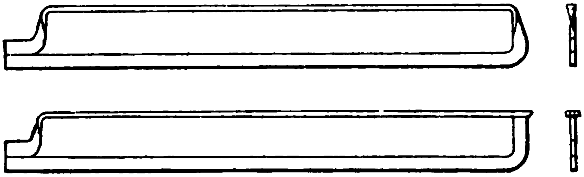


WINDING DIAGRAM. RING ARMATURE.

For arc-lighting armatures, and in general those which have numerous convolutions of wire to each section, it is convenient to prepare the wire in separate lengths sufficient for each section, and to coil each length on small shuttles, each length being wound upon two shuttles, which are alternately used for successive layers. By this device both ends of the wire that constitutes a section are brought to the outside instead of one of them leading directly down to the bottom layer, as in ordinary bobbin winding.

For those machines that only require one, or two, complete turns to each section, it is common to have the copper conductors prepared beforehand upon separate formers, and ready taped to be slipped on over the cores. Crompton introduced the forms illustrated in Fig. 255, consisting of

FIG. 255.

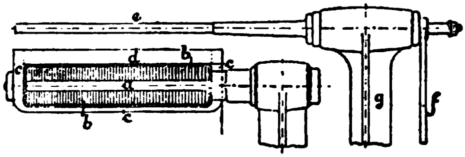


WINDINGS OF CROMPTON'S ARMATURES (1886).

drawn copper of nearly rectangular section twisted at the ends so as to pack closely in the interior of the ring. These conductors are sprung on over the ring core, with appropriate insulation between them, and afterwards coupled up so as to make a continuous winding.

In the large multipolar ring dynamos with internal field-magnet and external commutator, now so much used for central stations in Germany, the windings are so constructed that their outer part serves also as commutator, as in Plate XI., Fig. 3. The ring consists of core-disks built up of segmental plates, shown in section at *b*, Fig. 256, supported by driving-

FIG. 256.



CONSTRUCTION OF GERMAN MULTIPOLAR RING ARMATURE.

rods *a* which pass through them. After being covered with suitable insulation, the copper conductors *c d* are slipped on over them, and coupled up to make a continuous spiral winding. The insulation between, as used by Siemens and Halske who introduced this type, is a preparation of paper.

The outer part *d* of the copper conductor is made both deep and broad, and serves as a commutator bar. The brushes (not shown) are fixed upon the projecting bar *e*, and trail on the outer periphery of the copper windings of the ring. At *f* is a lever for raising the brushes out of contact.

Drum Winding.—Drum armatures of all types may all be regarded as modifications of Siemens' well-known longitudinal shuttle-form armature of 1856, a multiplicity of sections of the coils being employed to afford practical continuity in the currents. The drum pattern was invented in 1872 by von Hefner Alteneck, of the firm of Siemens and Halske, of Berlin. In this system, as in the Gramme ring the successive " sections " or groups of coils that are wound on the core, are connected together continuously, the end of one section and the beginning of the next being both united to one bar of the commutator. It is important to note the difference between this and the ring winding. In a ring winding the volts induced in any one section (at a given speed) depend only on the magnetic field at one side of the armature; but in a drum winding the volts induced in any one section depend on the two magnetic fields at the two sides, since each winding wraps over the drum nearly diametrically. As a result, drum-wound armatures are less liable to spark; and they possess a smaller self-induction than ring windings.

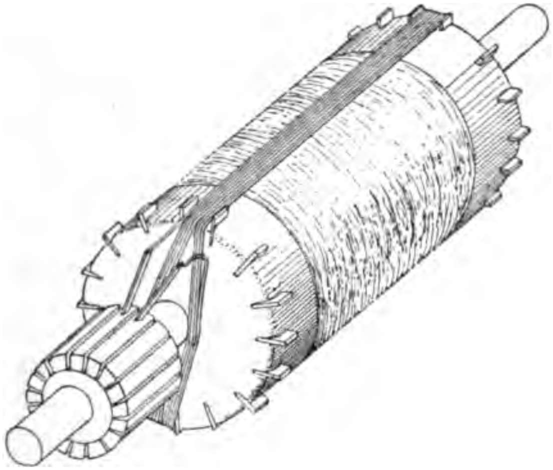
The advantages of the drum form of armature appear to be (1) that they require somewhat less wire than the ring armature of equal size: (2) are free from liability to false inductions, p. 433), and therefore more independent of the form of the pole-pieces; (3) have smaller cross-magnetizing tendency than ring armatures. Their disadvantages hitherto have been: (1) greater difficulty of construction; (2) greater difficulty of securing proper insulation on account of overwrapping of conductors; (3) greater difficulty of ventilation; (4) greater difficulty of executing repairs.

Siemens' Dynamo.—In some of the earlier patterns of Siemens' machines the cores of the drum were of wood, overspun with iron wire circumferentially before receiving the longitudinal windings. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. The process of constructing the armature employed down to the year 1885 is shown in Fig. 257. Upon the axle are secured by pins two stout cheeks of gun-metal to form the ends of the drum. Between these, and resting on an inner projecting rim, is wrapped a thin sheet of iron, and over this a quantity of soft iron wire is wound to form a core, as in the Gramme armature. A number of cuts, equal to the proposed number of segments, are sawn radially in the end faces of the gun-metal cheeks, and in these cuts small boxwood wedges are inserted to facilitate the winding. The coiling of the sections is done in the following manner:—The wire is carried along the drum, as shown, four of the strands passing to the left, four to the right of the axle at either end, and is then ready to be turned over to meet the connecting piece of the second segment of the commutator. From this point the next section will start in a like manner; but before the second section is wound the drum is turned completely over, and the section diametrically opposite to section No. 1 is wound on the top of the eight strands already wound. Thus, in a 16-part armature, section No. 9 lies on the top of section No. 1, No. 10 on the top of No. 2, and so on, there being two layers of coils all over the drum. The two layers must be thoroughly insulated from one another, to ensure that parts which are at very different potentials shall never come in contact with one another. Although, for the sake of rendering the connexions more intelligible, the commutator is shown in Fig. 257 in its place on the axle, it is not, as a matter of fact, put into its place until after all the sections have been wound, the ends of the wires being temporarily twisted together until all can be soldered to the connecting strips of copper. In some of the armatures intended for electro-plating machines there are four layers of wire, and the wires are connected together four or eight in parallel to reduce the resistance.

So far all is simple, but when we pass on to the construction of bar armatures, new complications arise.

To connect the conductors of a bar armature across the ends of a drum is not so simple a matter as might at first appear. Suppose that a scheme of connexions has been worked out beforehand in one of the ways described in Chapter XII., and that a winding-table has been prepared in which the order of the end connexions is set down. It yet remains to determine the mechanical devices for the end connexions which shall be compatible with working conditions. The end connectors must be good conductors, sufficiently well insulated from one another, allowing of repairs and ventilation, and mechanically sound. Wire-wound drums present an ugly over-wrapping at the ends, which stops ventilation and hinders repairs. Quite early, Messrs. Siemens devised, for their electro-plating machines, a system of uniting by spiral connectors the ends of the copper bars. To connect any bar with that lying next to the one diametrically opposite, two spiral strips of copper were applied, one bending inwardly, the other outwardly, their junction being mechanically secured to a block of wood on the shaft. Their outer ends were attached

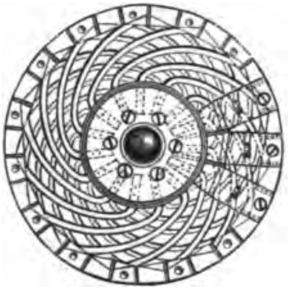
FIG. 257.



METHOD OF WINDING SIEMENS' ARMATURE.

to the bars by silver solder. At each end of the drum thes spiral connectors constituted two separate layers. Thes systems of spirals, with more or less modification, are to b found in the majority of recen drum armatures.

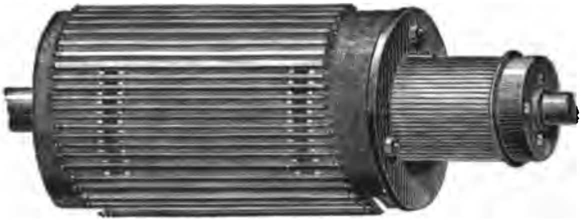
FIG. 258.



SIEMENS BAR ARMATURE.

In Edison's modification of th drum armature, the winding though symmetrical in one sense is ' singular, inasmuch as th number of sections is an od number. In the first machine there were seven paths, as show in Fig. 208, p. 319, taken fro Edison's British Patent Specification. In his giant "steam dynamo" (1883) the number of sections was forty-nine. One consequence of this peculiarity o structure is, that if the brushes are set diametrically opposit to one another, one will touch the middle of a bar of the commutator at the instant when the other slides from bar to ba In Edison's larger dynamos, the armature is constructed o solid bars of copper, arranged round the periphery of a cor consisting of thin iron disks separated by mica or paper. Fi 259 shows the armature removed from the machine. The en of the bars are connected across by washers or disks of copp insulated from each other, and having projecting lugs, t which the copper bars are attached. Such disks present mu

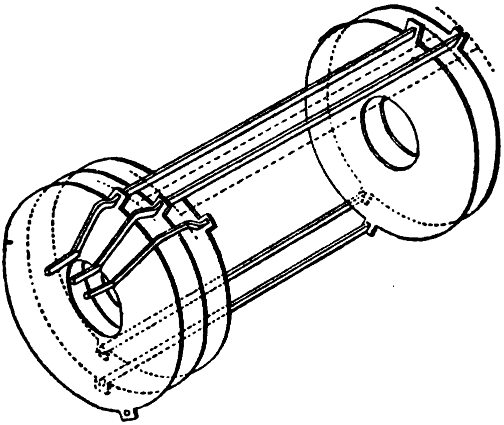
FIG. 259.



ARMATURE OF EDISON DYNAMO.

less resistance than mere strips would do. To make the mode of connexion plainer the diagrammatic sketch of Fig. 260 is given. The connexions are in the following order:— Each of the forty-nine segments of the commutator is connected to a corresponding one of the forty-nine disks at the anterior end of the drum; and this disk is connected, by a lug-piece on one side, to one of the ninety-eight copper bars. The current generated in this bar—say, for example, the highest of the three bars shown in Fig. 260—runs to the farther end of the machine, enters a disk at that end, crosses the disk, and returns along a bar diametrically opposite that along which it started. The anterior end of this bar is attached to a lug-piece of the next disk but one to that from which we began to trace the connexions: it crosses this disk to the bar next but one to that first considered, and so round again. The two lug-pieces of the individual disks at the anterior end are, therefore, not exactly opposite each other diametrically, as the connexions advance through $\frac{1}{49}$ of the circumference at each of the forty-nine paths. To simplify matters, in the drawing the alternate disks and bars are only indicated in dotted lines. Just as the two bars shown at the

FIG. 260.

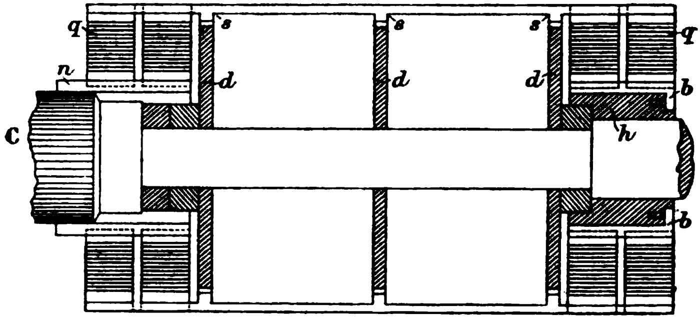


CONNEXIONS OF EDISON ARMATURE.

bottom are the returns for the currents in the top bars, s there must be top bars provided as returns for the currents i those bars (not shown) which start from the segments of th lower half of the collector. The dotted lines show th position of these return bars. The construction is mechan cally excellent, but it does not admit of ventilation ; and th stray field at the ends of the armature is liable to set u eddy-currents in the substance of the copper disks.

In the Edison-Hopkinson armatures built by Mather an Platt, Edison's device has been abandoned in favour of system of spiral connectors, as already described on p. 36 The construction of Hopkinson's armature, as carried out fo a machine in which there is one convolution in each section c the winding, is indicated in Fig. 261.

FIG. 261.



SECTION OF HOPKINSON'S DRUM ARMATURE.

The core, which is built against a shoulder on the shaf consists of numerous disks of thin iron, but with a few thicke core-disks, *d*, *d*, interposed at the ends and at intervals betweer These are clamped up by nuts at the end near the commutato C. The conductors of copper are provided with driving lug *s s*, which, properly insulated, project into notches cut in th thick core-disk. The systems of spiral connectors are show in section at *q q*. At the commutator end they join the con ductors down to a set of copper pieces *n*, which run to th corresponding bars of the commutator. At the other end the spirals are inserted into a set of copper pieces *b* assembled around a wooden hub *h* by which they are driven, being screwed in through end lugs. For armatures in which each section consists of two convolutions, it is necessary to provide four layers of spiral connectors at each end.

Many successive modes of drum connexion have been tried by Mr. Crompton. In conjuction with Mr. Swinburne he devised a method of connecting the conductors of a drum armature which enables the core to be ventilated. The fundamental point in this construction is illustrated by the simple form sketched in Figs. 262 and 263. There is only one layer of conductors outside the core, and these consist of copper wire of narrow rectangular section set edgeways. Every alternate conductor of the set is bent radially inwards for a certain distance, and then recurved outside again parallel to the axis of the drum. The conductors that lie between them are prolonged straight outwards to a certain length. The result of this arrangement is that there are two concentric sets of projecting ends. Connexion is made by a spirally-bent strap of copper from the ends of one of the outer straight set to one of the inner recurved set; for

FIG. 262. FIG. 263.

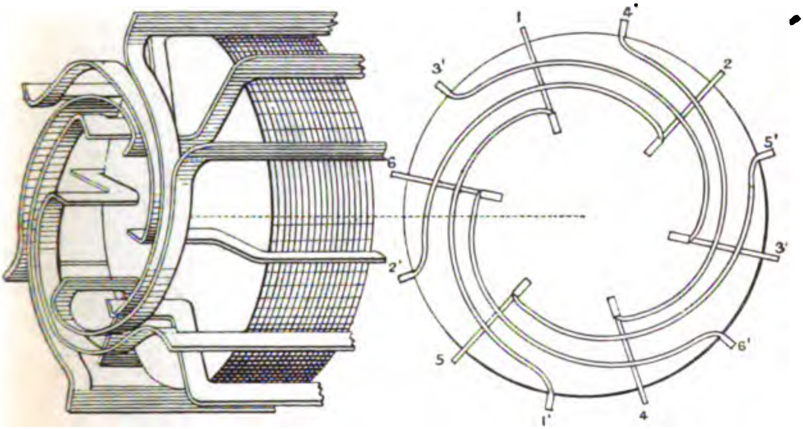
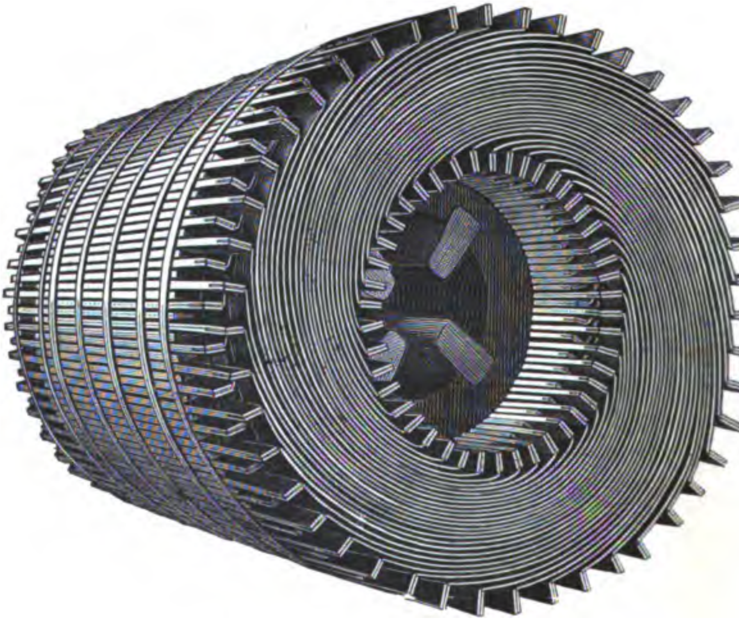


DIAGRAM OF CROMPTON AND SWINBURNE'S METHOD OF DRUM WINDING.

example, to the one that lies next to that at the diametr
cally opposite point of the periphery. In Figs. 262 and 26
which depict the connexions at one end of a simple six-par
armature (the six-part commutator at the other end is no
shown), conductor 1 is connected in this manner to conducto
1′. At the other end of conductor 1′ (not shown) there woul
be a similar cross-connexion to the far end of conductor 2
and the near end of 2 is joined to 2′; and so forth. Or th

FIG. 264.



CROMPTON AND SWINBURNE'S DRUM ARMATURE.

same method of connecting by spiral straps may be applie
to winding across a shorter chord, as on Swinburne's plan o
chord winding (p. 304). The method of connecting by spiral
of copper differs from that adopted in the Siemens electro
plating dynamos, Fig. 258, p. 364, in the use of the cranke
pieces. In the actual construction of large drum armature
the Crompton and Swinburne construction is more complex

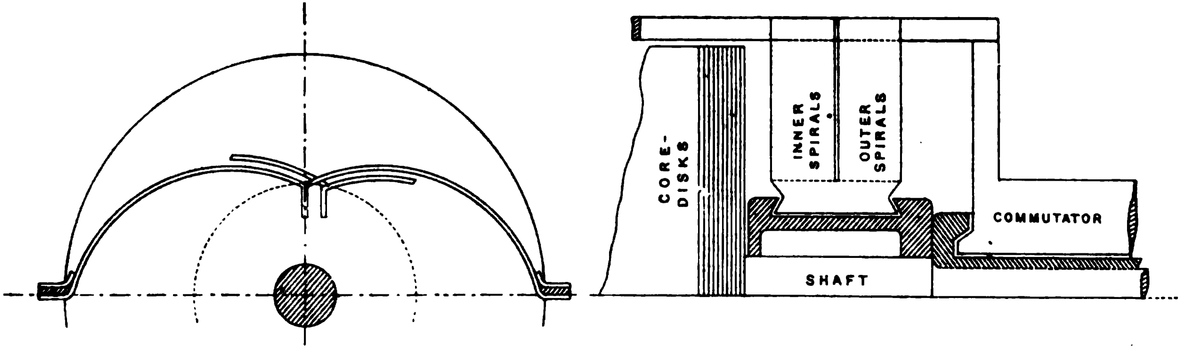
as it is impossible with a very large number of conductors to find room for all the spiral connectors in one whirl. Accordingly, there are two separate layers of spiral conductors, the projecting extremities of the conductors at the ends of the drum being themselves made alternately long and short, the short projections being connected by one layer of spirals, and the long projections being connected by another layer of spirals. The armature as so constructed is depicted in Fig. 264. The difficulty of getting at the inner spirals in this construction led to another suggestion by Crompton and Kyle, namely, turn the spiral connectors outward instead of inward, at the ends of the drum, which thus becomes enlarged in diameter.

The present modes used by Crompton for drum armatures are sketched in Figs. 265 and 266.

In the first of these, which is for a 2-pole dynamo, the spiral connectors, stamped out of sheet copper, are driven by mechanical attachment to a clamping sleeve keyed to the shaft. In the second, which is for a 4-pole machine, the spiral connectors, being shorter, do not require to be similarly tongued. The conductors are made of stranded wire compressed to rectangular section.

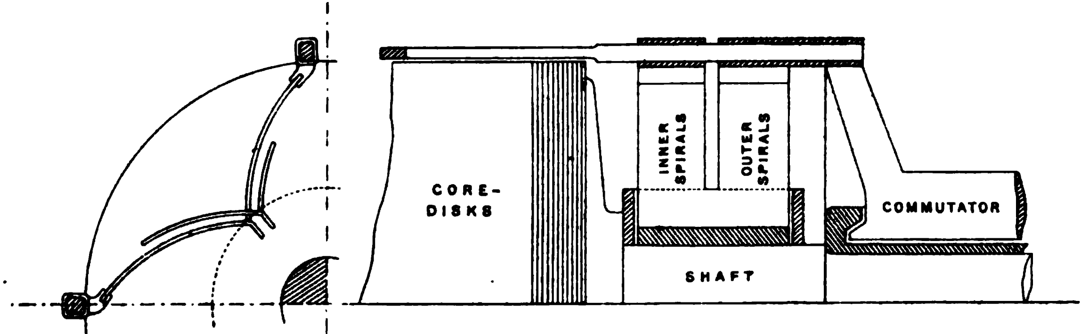
A method based on that of Paris and Scott is used by Kapp both for bipolar and multipolar drums. The connectors are stamped out from this sheet copper in the form of semicircular or quadrantal arcs, provided with lugs (as shown on Plate II., Fig. 2) which can be bent, one forward, one backward, thus enabling connexions to be made by a whole series of such connectors arranged skew-wise, with suitable insulation between, in a carriage or bobbin mounted on the shaft. The connectors are assembled together to the proper number, and held in with binding wires in the channel of this carriage, which is then put in place, and the lugs are soldered into grooves cut in the ends of the armature conductors, which, for this purpose are made alternately long and short at their ends. The best way to understand this method is to make a few model connectors in paper or cardboard, and lay them over one another.

Fig. 265.



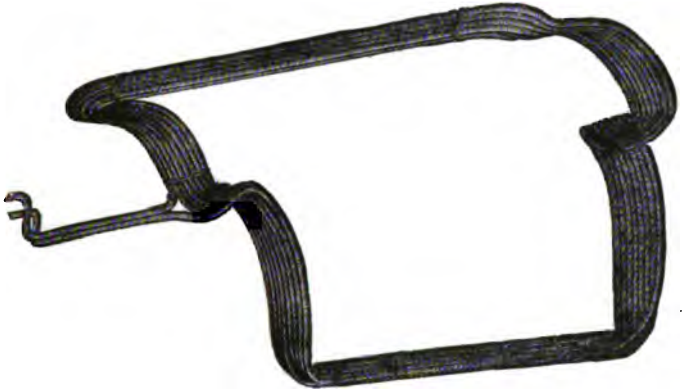
Crompton Drum Winding for Central Station Machine, 2-pole Dynamo.

Fig. 266



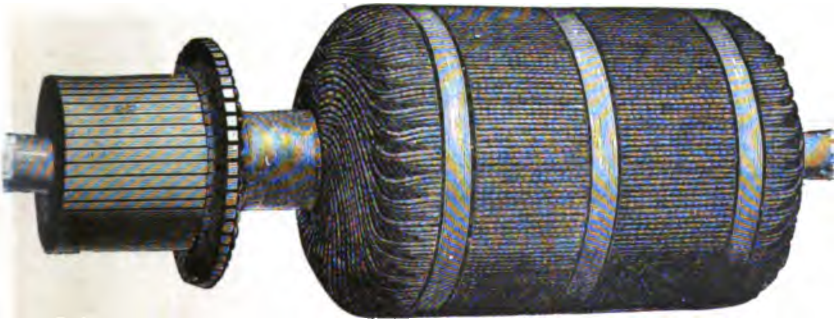
Eickemeyer's mode of construction differs from the preceding, in being applicable both to wire-wound drums and to strip-wound drums. In it, each section, whether consisting of many convolutions or of only one, is first shaped upon a separate former, and each such section is separately insulated. Fig. 267 shows the form given to the sections. The lower part will form part of an inner layer, and the upper part, which is longer, will form part of an outer layer in the assembled windings. The completed armature, with its binding wires, is shown in Fig. 268. The narrow neck between the drum and

FIG. 267.



SEPARATE SECTION OF EICKEMEYER'S ARMATURE.

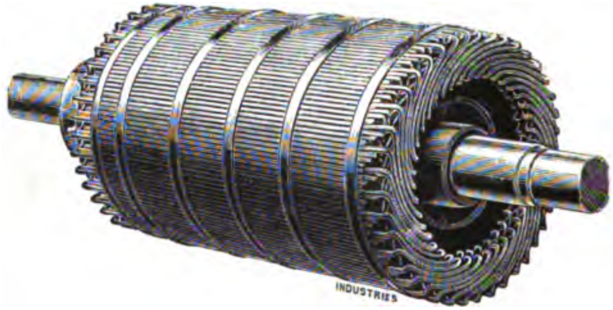
FIG. 268.



EICKEMEYER'S ARMATURE, COMPLETE.

the commutator is necessitated by the form of field-magnet (Fig. 128, p. 203) adopted in this machine. The Eickemeyer winding has also been adopted by the Edison Company[1] in its recent machines.

FIG. 269.



ALIOTH'S DRUM ARMATURE.

Fig. 269 depicts a drum armature by Alioth, of Basel having four layers of spirals at each end, designed for a 4-pole field.

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[1] See *Electrical World*, xvi. 249, 1890.

CHAPTER XIV.

COMMUTATORS, BRUSHES, AND BRUSH-HOLDERS.

DYNAMOS for furnishing direct currents require a *commutator* (sometimes called a *collector*) and *brushes* to collect the current. The essential action of these organs has been already described (see pp. 39 and 84); and the causes that give rise to sparks are discussed in Chapter IV., p. 83, and in Chapter XVI. We have now to consider the design and construction of these organs.

We may distinguish three types of apparatus for collecting the currents from dynamo-machines.

I. Direct-current dynamos with closed-coil armatures, as used for incandescent lighting and other work requiring a constant or nearly constant potential, are furnished with a commutator of the Pacinotti type, that is to say consisting of a considerable number of parallel bars secured around an insulating hub, and presenting a cylindrical surface, against which press a pair (or in some cases more than one pair) of brushes or sets of brushes.

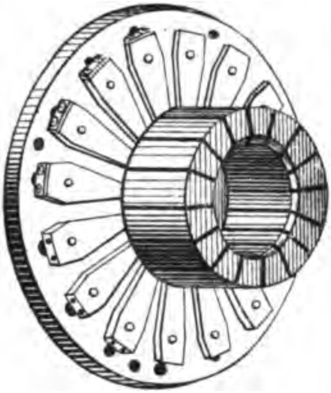
II. Direct-current dynamos of the open-coil type, as used for arc lighting, and giving a constant or nearly constant current, are provided with a commutator consisting of a comparatively small number of segments, each covering a considerable angle, and separated by air-gaps from one another. These are described in Chapter XVII.

III. Alternators with revolving armatures need a pair of collecting rings of metal, each provided with one or more brushes, or some analogous device to form a sliding connexion with the circuit. Alternators with revolving field-magnets need a similar device to convey the exciting current to the moving coils. These devices are considered at the end of the present Chapter, which is in the main devoted to apparatus of the first of the three classes enumerated.

Commutator Bars.—The number of bars of the commutator depends on the scheme of winding and on the number of sections in which the armature winding is grouped. Increasing the number of bars diminishes the tendency to spark (p. 87); and lessens the fluctuations of the current, (p. 221.) An even number of bars is preferable to an odd number; and for ring-wound armatures the cores of which are usually carried on three-armed spiders, it is preferable that the number of bars should be a multiple of three. There are however, two practical reasons against making the number of bars very great. Increasing the number increases the cost. Again, in large machines having but one turn of the armature winding from each bar of the armature to the next, the number cannot be greatly increased without exceeding the voltage desired. For example, in an Edison-Hopkinson machine for an output of 1100 amperes at 105 volts, only 43 convolutions are required. On the other hand, it is found for small dynamos, that if the number of bars is increased, each bar becomes so thin that a brush of the proper thickness to collect the current would bridge more than two commutator bars at once. Again, the bars should be of a length proportioned to the number of amperes that is to be taken off at them. Modern practice varies somewhat, but it may be fairly represented by some such figure as 1·2 inches for every 100 amperes. The mode of attachment of the bars should be such as to make the greatest amount of length available. They should also be of considerable radial depth, to allow for wear, as the commutator needs to be turned down from time to time to preserve cylindricity. As for the material most makers use hard-drawn copper, made in long lengths of the proper section, and cut off to the length required. Some American makers use drop-forgings of copper, stamped to shape with projections for clamping and connecting to the windings. Crompton has used phosphor bronze, but now casts a special alloy of copper containing a very small percentage of silver.

Insulation.—It is needful to have a good insulation between each bar and its neighbours, and a specially good insulation between the bars and the sleeve or hub around which they are mounted, and also between the bars and the clamping devices that hold them; for the difference of potential is small between neighbouring bars, and much larger between the bars and other metal-work. The insulating material must not absorb oil or moisture: hence asbestos and plaster are inadmissible. Vulcanized fibre and Willesden paper are not by themselves adequate, though mechanically strong. Mica is the only satisfactory material. Commutators with air-gaps between the bars have been used by Ayrton and Perry, by Hochhausen, and by Siemens and Halske (p. 508). In Hochhausen's machine the commutator (Fig. 270) consisted of L-shaped bars bolted to a disk of slate. The trouble with air-insulation is to keep the gaps from being filled by metallic dust from the wearing of the brushes.

Fig. 270.

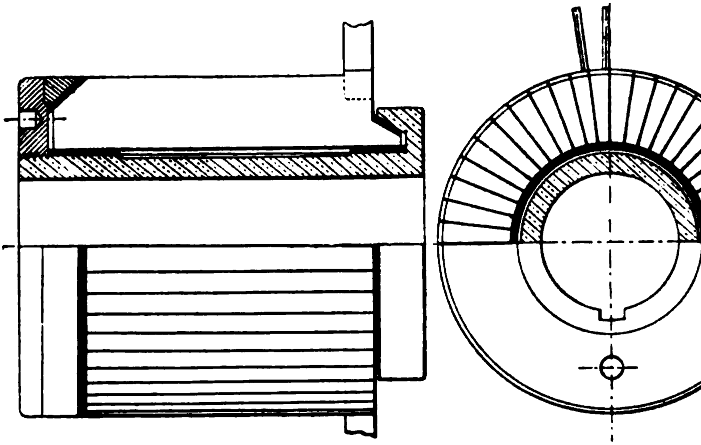


Commutator of Hochhausen Dynamo.

Construction of Commutators.—Fig. 271 shows the construction adopted by Messrs. Paterson and Cooper. The bars are clamped in place by fitting at one end into a groove in a gun-metal sleeve, and at the other by an external clamping ring which is forced over their bevelled ends by a large screw-washer. The insulation is carried out by thin slips of mica between the bars, and layers of mica and vulcanized fibre around the sleeve and clamping surfaces. The clamping ring in this case reduces the available surface for the brushes.

In the Gülcher Co.'s machines a construction is ad which is illustrated by Figs. 272 and 273, and of whi section is given in Fig. 274. The drawings relate to a 4 machine with only two sets of collecting brushes. Here the bars of the commutator are assembled around a s fixed on the shaft, but are so arranged that their whole l is available for contact with the brushes; being he

FIG. 271.



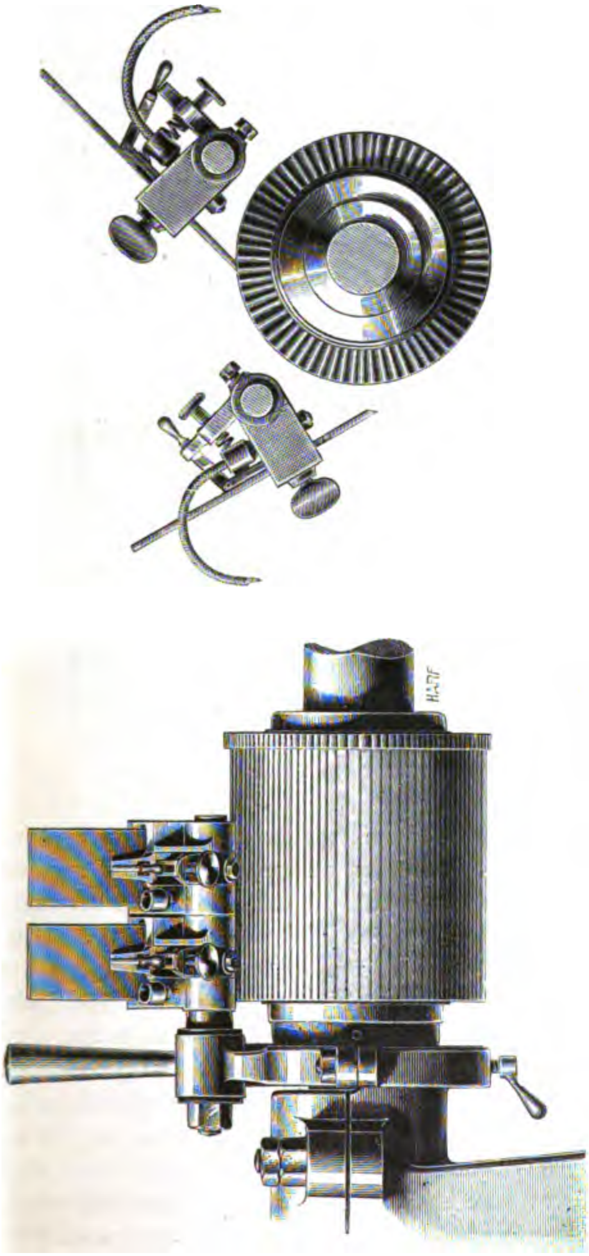
PATERSON AND COOPER'S COMMUTATOR.

position at their ends, with insulation between the V-sh nicks in the bars and the clamping pieces which enter th

A very similar arrangement obtains in Kapp's dy (Fig. 1, Plate II.), in which the clamping nicks in the of the bars are made deep; the end insulation being eff by three rings of vulcanized fibre, one flat the other two co which fit into the ends of the assembled bars. It is good a sufficient length of insulating surface should exist bet the bars and the metal mountings, for, as in the ca telegraph insulators, there is less likelihood of a fault o ring if the possible leakage-path over a dirty surface is a path, than if it is short.

In building commutators it is usual to assemble the to the proper number, with the interposed pieces of

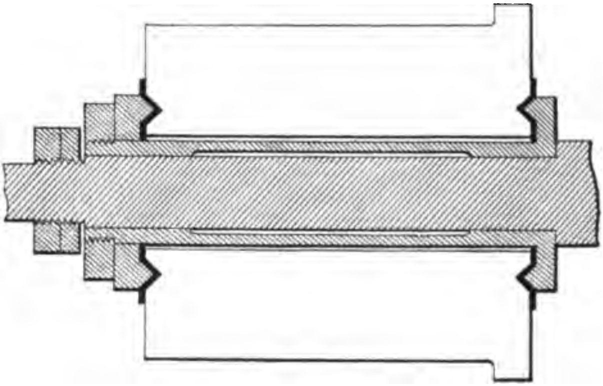
FIGS. 272 and 273.



COMMUTATOR AND BRUSH-HOLDERS OF GULCHER CO.'S 4-POLE MACHINE.

clamping them temporarily around the outside with a stror iron clamp, or forcing them into an external steel ring b hydraulic pressure. They are then put into the lathe and tl interior cylindrical surface is bored out. Then the ends a turned up, with the annular hollows to receive the clampir pieces. The whole is then mounted, with proper insulatio upon the sleeve, and the end clamping pieces are screwed u It is then heated in a stove, and the end clamping pieces a further tightened up. Lastly the temporary external clam

FIG. 274.



GULCHER CO.'S COMMUTATOR. (Section.)

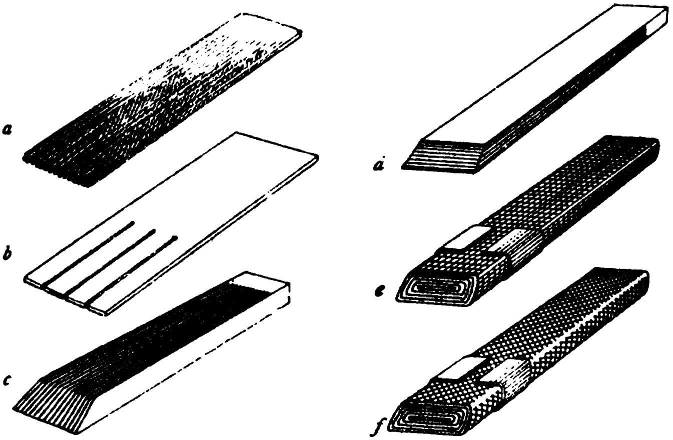
or rings are removed and the external surface is turned true. The sleeve should be properly keyed or otherwi secured to the shaft, that there may be no slip between it a the armature to which it is afterwards connected. In all tl last forms depicted, connexion is made with the armatu conductors by means of strips or wires of copper, which a inserted into a cut sawn in the corner of each bar, and firm held there. A good mode is to rivet the strip connectors in the corners of the bars before they are assembled, each rivet joint being also sweated in with solder.

It is important that these connecting strips should properly attached, since they are subjected to considerat mechanical forces. Twice in each revolution each such str carries a strong current; and, owing to the existence of a stray magnetic field, is consequently racked toward one side. Before this was understood it gave rise to frequent accidents.

In some large recent machines there is no separate commutator; the brushes trailing against some part of the copper conductors of the armature winding themselves. This is the case with the great Siemens dynamo at Berlin (Plate XI. and Fig. 256, p. 360); the Edison Company's multipolar dynamo (Plate XIII.); and the Willson dynamo.

Brushes.—The kind of brush most frequently used for receiving the currents from the collector, consists of a quantity of straight copper wires laid side by side, soldered together at one end, and held in a suitable clamp. The number of points of contact secured by this method is advantageous in reducing sparking. Two layers of wires are often thus united in a single brush, as shown in Fig. 275 *a*.

FIG. 275.



DIFFERENT KINDS OF BRUSHES.

Brushes are also made of broad strips of springy copper slit for a short distance so as to touch at several points, Fig. 257 *b*. Such are used in the Brush and Thomson-Houston arc-light dynamos. This kind of brush is usually set ta gentially to the surface of the commutator; not sloping to at an angle as is the case with the thicker kinds of brushes.

Edison has used as brushes a number of copper stri placed edgeways to the collector, and soldered flat against o another at the end furthest from the collector, Fig. 275 *c*. He also, the object in view was the subdividing of the spark the contact. In some of the Edison machines, a compou brush made up alternately of layers of wire, like Fig. 275 and slit strips of copper, like Fig. 275 *c*, has been adopted.

Other makers have used a number of very thin copp strips laid over one another as in Fig. 275 *d*, held together a suitable clamp.

During the past few years gauze brushes have come in fashion, sheets of copper wire gauze being rolled up a compressed as in Fig. 275 *e*. In order to avoid fraying at t front edge it is usual to fold the gauze obliquely, as in Fig. 2 *f*; the wear is then more uniform. Rotating brushes in t form of metal rollers or disks were first used by Holmes (s p. 11), and have also been tried by Gramme, and others ha been suggested by Sir W. Thomson and Mr. C. F. Varley.

It was suggested[1] by Professor G. Forbes to replace t brush by a slab of fine-grained and good conducting carbo Carbon brushes are indeed used now frequently, both f dynamos and for motors.

It is usual, for all but the very smallest machines, to pla at least two brushes side by side (as in Fig. 330, p. 48 instead of one broad brush. This allows of either bru being removed for trimming and replaced, while the machi is running. It also tends to equalize the wear of the co mutator, each brush being separately pressed against t surface. No rule can be given for the number or breadth brushes that will apply to all cases. Some makers reckon additional inch breadth of brush for each hundred amperes output. Nor is it easy to give a general rule for the thickne of brushes. A thickness that will bridge the film of insulati between bar and bar is not sufficient, for each section of t winding requires to be short-circuited for a certain brief time, in order that the current in it may be reversed. The minimum thickness of brush (or breadth of its oblique end) seems to be about 1½ times the thickness of the commutator bar. There is no objection to a greater thickness in those dynamos that have a large neutral zone about the neutral point, or in which the curve of induction (Fig. 55 p. 70) has a broad flat top. But when a brush of great thickness is used another effect arises, namely, a waste in heating owing to the difference of potential between the parts of the commutator respectively in contact with the advance edge and hinder edge of the brush. To reduce this effect it has been proposed to use two thin brushes, one in front of the other, instead of a single thick one, with a certain amount of resistance between them. Messrs. Goolden & Company have used wire brushes with the separate wires oxidized so as partially to insulate them one from the other, their distant ends only being soldered together.

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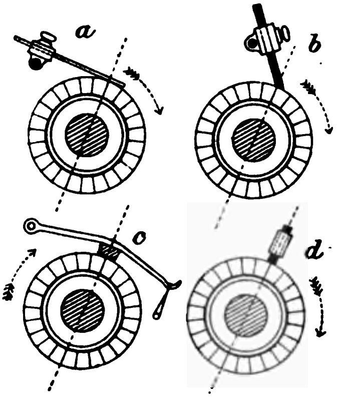
[1] Specification of Patent 1288 of 1885.

FIG. 276.

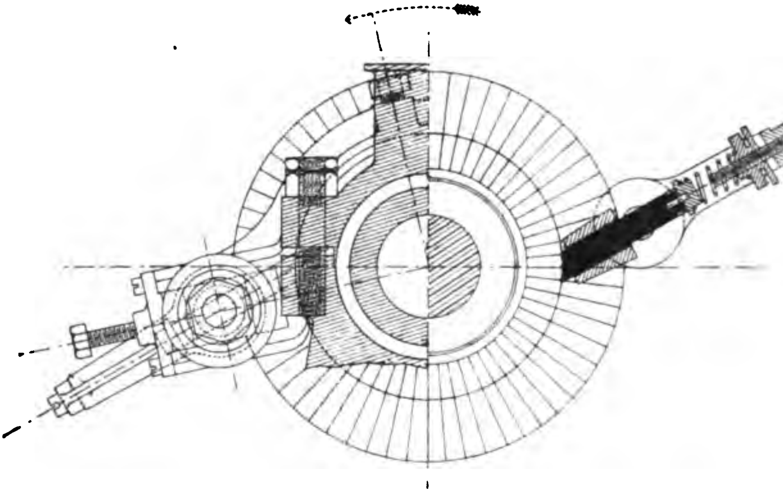


VARIOUS COLLECTING BRUSHES.

The angle at which brushes are set to bear upon the commutator varies with the construction. As a rule the brush is set sloping at an angle, the tip of the brush being raked in the direction of the rotation, so that it may not trip on the edges of the commutator-bars In Fig. 276 *a*, is shown the case of a brush such as Fig. 275 *b* set tangentially, as in arc-light machines. In Fig. 276 *b* is a thick brush with bevelled end set at about 45°, as in most constant-pressure dynamos. Fig. 276 *c*, shows a form of brush devised by Holroyd Smith for use in motors, permitting of reversal of direction. Blocks of copper or gunmetal are attached to levers furnished with rubber bands to afford contact-pressure. In Fig. 276 *d*, is shown a carbon brush also adapted for use in reversing motors; the brus a rectangular block of carbon, being pressed radially throug a metal slide against the commutator.

In many cases where carbon brushes are used they are s to rake in a direction opposite to the rotation, so that the en pressure may be greater when running. Fig. 277 illustrat

FIG. 277.



CARBON BRUSH-HOLDER.

the form of carbon brush-holder designed by Mr. A. T. Sn for use in mining motors.

Brush-holders and Rockers.—The mechanism for holdi the brushes must fulfil certain mechanical and electric conditions; they are as follows:—

(1.) The brushes must be held firmly, and joined with good metallic contact to their circuit.
(2.) Brush-holders must permit brushes to be withdra or fed forward as required.
(3.) Brushes must be held to make contact at prop angle to the surface of the commutator.

(4.) Brushes must bear with proper pressure upon the commutator; if too light, they will jump and spark; if too heavy they will cut the commutator into ruts.
(5.) Brush-holders must permit brushes to be raised from contact.
(6.) They must also permit, by a proper mechanical catch, of the brushes being held raised out of contact.
(7.) Insulated handles should be provided for all dynamos working above 100 volts, so that the brushes may be raised and adjusted without risk of shocks.
(8.) The insulation of the brush, or of brush and brush-holder together, must be very thorough.

A characteristic example of brush-holders is afforded by those of the Gülcher Company's machine, Fig. 273, p. 377. This is a four-pole machine (cross-connected), and therefore the two brushes must make contact at two points 90° apart. A very similar example, designed by Mr. W. C. Mountain for the "Tyne" dynamo, is given in detail in Plate XV., which also shows the construction of the commutator and the rocker. The rocker R, in Figs. 1 and 2 of this plate, consists of a wrought iron ring in two parts, which is clamped together by bolts upon a raised rim on the bearing. To this rocker are attached a handle H for shifting it so as to bring the brushes to the neutral point, and a couple of projecting lugs L (one only shown) to carry the brush-holder rods, M. The latter are mechanically secured to the rocker lugs by screw nuts which hold them tightly; but they are electrically kept from making contact with the rocker by the interposition of an insulating bush and washers of ebonite. Upon the rods M are placed the brush-holders A, which can turn hinge-wise upon them. Between the hinges of A is fixed, by a screw F, a middle piece D with a projecting tail. The brush B passes through a slot in A, being clamped by a screw C. The current is brought to the brush-holders by flexible conductors, which are soldered into sockets provided for the purpose. The brush is pressed forward by a compressed spiral spring, the force of which can be regulated by a screw through the projecting tail of D; whilst it can be held off by means of the catch K, which can be pulled back and slipped into a cleft on the end of D. In Fig. 273, p. 377, which depicts the similar mechanism of the Gülcher dynamo, one of the hold-off catches is caught in the cleft.

The rocker and brush-holders of the Phœnix dynamo are depicted in Plate XV., Figs. 4 and 5. The method of insulating is here the same, but the requisite pressure is obtained by coiling a spring around the rod ; and the holding-off catch is a pin which can engage in a cavity in the rod.

The rocker and brush-holders of the Kapp 2-pole dynamo are shown in detail in Plate III. Here the mode of insulating is the same, but the current is led into a thick washer G ; the contact-pressure is produced by an extended spiral spring stretched between a lug on the holder A and the fixed tail D ; and the hold-off catch K is constituted by a straight spring which engages in a notch on the corner of A and is released by pressing up the piece Q, which is made o hard fibre. P is a pointer for setting the brushes to the right position in the holder.

A somewhat cruder example is afforded by the brush-holders of the Edison dynamo, Plate XIV., Figs. 1 and 2 in which there is no hold-off catch, but the brushes are raised when required to be held off, by turning the screw that tightens the contact-spring.

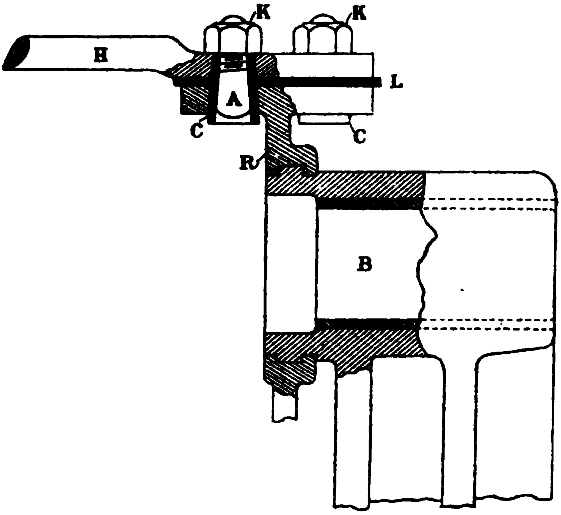
Another set of arrangements of brush-holder, rocker, and catches is depicted in Plate XIX., giving the details of the "Agir" motor.

A defect in the method of insulating by means of a bush upon the brush-holder rod, is its liability to permit the rod to turn. A more solid construction is that of Messrs. Barley and Stevenson, Figs. 278, who flatten out the end of the holder-rod H, and clamp it to an expansion of the rocker R by means of two conical bolts A ; insulation being secured by an interposed layer L, and two conical bushes C of ebonite or fibre

An excellent form of brush-holder; which permits the brushes to be fed forward longitudinally by a screw motion as required, has been devised by Messrs. Goolden & Co., and has a cam-motion for holding-off.

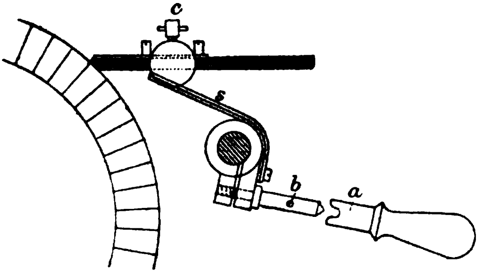
Various inventors have tried to simplify the construction; amongst them, Parsons has proposed to substitute weights for springs to give the requisite pressure.

Fig. 278.



BARLEY AND STEVENSON'S INSULATED BRUSH-HOLDER ROD.

Fig. 279.



SIEMENS AND HALSKE'S BRUSH-HOLDER.

A very simple and effective form of brush-holder, introduced by Siemens and Halske, is used largely in Germany. In this form, Fig. 279, the clamp which holds the brush is set on the end of a curved support *s* made of several thic nesses of springy sheet brass. This is simply clamped to t holder-rod by a clamp screw *b* which admits of the holder bei shifted along the rod, or of being turned to give greater or le pressure. The tool *a* is used for any of the required adju ments. These brushes are used with the large multipol dynamos, such as that figured in Plate XI.

BRUSHES AND COLLECTORS FOR ALTERNATORS.

Alternators have no commutator, but they usually ne a pair of sliding contacts to convey the currents to and fro the rotating part. The usual device is a pair of contact rin of copper or gun-metal mounted on insulating hubs on t shaft, with one or more brushes to press on each contact-rin In those alternators in which the revolving part is the arm ture, great care must be taken to insulate well the two rin from each other, and from the shaft. A deep projecting r of ebonite should be provided between the two rings if th are situated on the same side of the machine, as in the Blake Emmett alternator, Plate IX. Fig. 3 and Plate XXI Fig. 1, or as in the Westinghouse alternator, Fig. 423, or t Hopkinson alternator, Fig. 425. In Kapp's alternat Fig. 421, the contact rings are on opposite sides of t armature, so that not only is high insulation easy, but t risk of accidental shock is lessened. Two brushes are oft applied to each ring, so as to admit of replacement wh running. In Ferranti's alternators there is a special collecti arrangement, Fig. 435.

In those alternators in which the revolving part is t field-magnet, contact rings and brushes are needed to bri in the exciting current. But, as the current is small and low voltage, the collecting arrangements are simple and ne no special care in insulation. In the slow-speed three-pha alternators constructed by Brown (Plate XXVIII., Fig. 1) t exciting current is conveyed in through two belts of flexil standard wire running over gun-metal pulleys.

CHAPTER XV.

MECHANICAL POINTS IN DESIGN AND CONSTRUCTION.

EVERY dynamo and motor being a piece of running machinery, it is needful to consider the mechanical rules that apply to the design and construction of the various parts.

In Chapter XIII. are considered the mechanical modes of transmitting the power from the shaft to the armature conductors and *vice versâ*. The design of dynamo shafts, journals, bearings, pedestals, and pulleys is a matter equally requiring a knowledge of mechanical principles and practice. Such standard works as Unwin's *Machine Design* should be followed. Nevertheless there are some points in which the ordinary engineering rules cease to be entirely applicable; and it is because of this circumstance that it seems desirable to give the information embodied in the present chapter.

Pressure on Bearings.—In addition to the ordinary pressures on bearings, due to weight of the shaft and its attachments, and to the lateral drag of the driving-belt, there is in dynamo-machines a third cause producing pressure, namely the actual magnetic pull which the field-magnets exert on the armature core. This is notably great in the case of dynamos having a single magnetic circuit. An example in which the field-magnet tends to lift the armature is afforded by those machines, such as the Edison-Hopkinson, Fig. 352, p. 519, in which the magnet stands over the armature; whilst contrary examples are furnished by machines in which the armature is above the field-magnets, as in the Kapp dynamo, Plate I., and Fig. 330. If the armature is perfectly centred there will always be a tendency to drag it in such a way as to make the entire magnetic circuit more compact. This can be partially obviated by placing it eccentrically, slightly below the centre of the bored polar faces in machines of the under-type, and slightly above the centre in the over-type. In Kap machine the downward pull is partly compensated by leavi the pole tips wider apart below the armature than they a above it; or by using cast-iron pole-tips below and wrough iron pole-tips above. This magnetic pull may amount to much as four or five times the weight of the armature. F example, in a dynamo built by the Alsacian Company[1] f an output of 60 kilowatts, the magnetic pull on the armatu was equal to a weight of no less 1500 lbs. (see Fig. 28 p. 432).

Gyrostatic Action of Armature.—Another point, whi arises only in the case of dynamos used on ship-board and motors running round a curve on a track, is the gyrostat action of the revolving armature, which tends always to ke its axis pointing in the same direction. Sir William Thomsc who first directed attention to this matter, has given[2] t following formula for the gyrostatic force on a bearing.

$$F = \frac{W k^2 \Omega \omega}{g l}:$$

where F is the force, in lbs.; W weight of armature, in lbs l length between bearings, in feet; g the acceleration gravity (32 feet per second); ω the angular velocity of t armature, in radians per second; Ω the maximum angul velocity of roll of ship, also in radians per second; k t radius of gyration of the armature in feet.

Example.—In a ship rolling 20°, with a periodic time of 16 secon a Siemens alternate-current dynamo (Fig. 426) running at 1300 rev lutions per minute; $W = 148$ lbs.; $k = 0{\cdot}7$ foot; $l = 1{\cdot}4$ fo Here $\Omega = 2\pi \times \frac{20}{360} \times 2\pi \div 16 = 0{\cdot}137$; and $\omega = 2\pi$ $1300 \div 60 = 136$. Then $F = 30{\cdot}6$ lbs. on each bearing, alt nately acting up and down at each roll, if the axis of the dynar lies athwart the ship.

It is evident from these considerations that it would inexpedient on ship-board to employ dynamos having armatures which resemble fly-wheels in form, if the pressure due to the weight of the armature were not relatively much greater. Drum-armatures of length greater than their diameter are preferable for ship-lighting.

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[1] *Electrical Review*, xxv. 292, 1890.

[2] See Jamieson on Electric Lighting for Steamships, *Proc. Inst. C Engineers*, lxxxix. Nov. 11, 1884.

Journals.—From what has been said it will be clear that caution must be used in applying the ordinary rules of machine design. It is usually assumed that journals are made larger for higher speeds, because of the necessity of getting rid, by the greater cooling surface, of the heat generated at the higher speed. But it is known that this assumption leads to the rule

$$l = \frac{\mathrm{F}\, n}{\beta};$$

where l is length in inches; F the force (in lbs.) on the bearing; n the number of revolutions per minute; and β a constant which, according to various authorities, may vary between 66,000 and 1,000,000. With such a variation, the rule is almost useless as a guide to design; moreover it takes no account of the diameter of the journal. In all good engineering practice the ratio between the diameter and length of a journal bears a relation to the speed. For slow speeds, such as 100 revolutions per minute, the length need be no greater than one diameter; whereas for speeds of 1000 and upwards the length is five to six diameters, and in high-speed fans sometimes as much as eight diameters.

From this we get the approximate rule:—

$$\frac{l}{d} = 1 + 0{\cdot}004\, n.$$

The rule given above, which is an ordinary one for mill-shafting, is known not to apply to crank-shaft bearings, where centrifugal force is of little importance, but where there come heavy alternately-directed thrusts and wrenches. Still less can it strictly apply to dynamo machines. In these, for the most part, the power is transmitted through a few inches of shaft from a pulley to the armature. The journal between these two parts, if the pulley is outside, is obviously sustaining a much severer wrench than the journal at the other end ; is in many dynamos made larger and longer than that at t commutator end.

The following data were principally furnished to Profess Perry by students of the Technical College, Finsbury :—

TABLE OF JOURNAL SIZES.

Dynamo and description of Armature.	Revolutions per Minute.	Distance between bearings (inches).	H.P.	Length l (inches.)	Diameter d (inches).	Ratio $l \div d$
Brush 2-lighter (ring)	1120	17	2	5 5	1·25 1·25	4 4
Edison (1882 type) (drum) 150-light	890	54	15	11 11	2·75 2·75	4 4
" Manchester " (ring)	1600	26	6	3·75 3·75	1·4 1·4	2·68 2·68
Elwell-Parker (drum)	1300	30	10·8	6	1·62	3·7
Elwell-Parker (drum)	630	53	45	9	2·5	3·6
"Victoria" (Mordey) (discoidal ring)	2000	10	2	4 3·25	0·7 0·7	5·71 4·6
Ferranti alternator (star-disk) (1883)	1700	28	10	9 5·25	1·5 1·25	6 4·5
Kapp	780	34	30	10 8·5	2·25 2·25	4·4 3·77
Brown	500	56	35	9·75 9·75	2·0 2·5	4·88 3·9
Ferranti alternator (1889)	120	85	1250	57	14	4
Mordey alternator (Field-magnet revolving)	500	53·75	100	13 13	4·5 4	2·88 3·25

The safe diameter for a journal to give requisite streng depends on the load tending to bend it, as well as on the me twisting-moment that results from the power transmitt through it. The diameter of a shaft is usually calculated fro the formula, applicable when there is no bending :—

$$d \text{ (inches)} = c \sqrt[3]{\text{HP} \div \text{revolutions per minute}} ;$$

where $c = 2·9$ for steel shafts.

The lateral loading of an overhung pulley, due to the belt, produces a considerable amount of bending. Taking the ratios of breadth of pulley to diameter which are usual in dynamo manufacture, it will be found that c ought to be taken as having a value variously estimated from 4·2 to 5·5.

Again, the spindle or shaft of a dynamo is subjected to bending by the weight of the armature, by the magnetic drag on its core, and in belt-driven machines by the lateral drag of the pulley. When running, it is also subjected to bending stresses if the masses it carries are not properly balanced. If the brasses of the bearings keep the journals in line, it is evident that all such actions tend to bend the shaft at definite points. In machines with discoidal armatures a greater length of shaft is free to bend than in those with drum and cylindrical ring armatures, which stiffen the middle portion.

By taking the bending moments due to want of balancing into account, Professor Perry shows that the dependence of length of journal upon speed, hitherto looked upon as good in practice, but having no basis in theory, is really explicable. His result is that for discoidal armatures,

$$\frac{l}{d} = n\sqrt{\mathrm{L}} \div 1000\,;$$

and for drum and elongated ring armatures,

$$\frac{l}{d} = (n\sqrt{\mathrm{L}} \div 3500) + 2,$$

where L is the length of the shaft between the middle parts of its bearings, in inches; and n, l, and d, as before.

Journals, if plain, are usually terminated by collars or raised shoulders, to bear against the brasses and limit end-play. In some forms of machine end-play is specially provided for, so as to cause an even wear at the commutator.

For dynamo spindles the most suitable material is steel, Bessemer steel being usually employed.

In some British machines, chiefly small ones, and others of American make, a shaft of the same diameter throughout is used, with collars shrunk on to prevent end-play. This is not good engineering. A shaft ought to be as thoroughly designed for its work as any other part of the machine. It is well recognized in machine design that where an axle has to bear a transverse load tending to bend it between the points of support, it must be thickest where the bending moment is greatest. One takes as a basis of calculation the diameter appropriate at the journals (found as above) and, assuming that the shaft is of circular section, calculates the diameters at the other parts by the rule that the diameter at each point should be proportional to the cube root of the bending moment at that point.[1] It must not be forgotten that where key-ways are to be subsequently cut for securing the spiders or other attachments, additional diameter must be given to admit of this without reduction of strength. An example of an excellent piece of design is afforded by the shaft of Brown's dynamo, Plate IV.; also by those of Kapp's dynamo, Plate II.; and of Mordey's (Victoria) dynamo, Fig. 336, p. 499.

In the first of these examples it will be observed how the armature spiders fit on over the middle portion of the shaft, and the whole is tightened up by a threaded nut against a collar on the shaft. The commutator is built up around another and shorter sleeve, which slips over a slightly reduced part of the shaft, on the other side of the collar. The pulley is within the bearing, not overhung.

In the second, the armature spider is a long sleeve of cast iron, which stiffens the middle portion of the shaft, and is held up by a threaded nut against a collar.

In the third, the armature spider is held between nuts. The pulley is overhung, with a very thick journal between it and the armature, and a thrust-bearing at the commutator end.

Bearings and Pedestals.—Bearings for dynamos are always made divided, so that the armature can be lifted from its bed, and usually with steps of brass or gun-metal seated in an appropriate pedestal. Those who are not familiar with this elementary part of machine design should examine the drawings of the pedestals and bearings of various machines; particularly those of the Kapp dynamo, Plate I.; of the "Agir" motor, Plate XIX.; and those of the Ferranti alternator, Plate XXVI. Where long bearings are used they are occasionally made of cast iron instead of gun-metal or brass. More often a soft-metal bearing is used; or rather a soft metal, such as that known as Babbitt's metal, is used as a lining for a step of gun-metal or cast iron; such anti-friction metal being cast into shallow recesses formed for that purpose in the hollow of the step. An alloy named "Magnolia" metal has lately been largely employed for bearings.

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[1] See Unwin's *Machine Design*, p. 147.

Thrust Bearings.—In all dynamos with disk or discoidal ring armatures, end-play is inadmissible; and thrust-bearings must be provided similar to those used on screw-propeller shafts with raised collars on the journals. Or, instead, the shaft may be constructed with shoulders somewhat deeper than usual at the journals, to bear against the brasses. The reader should examine the various thrust-bearings in the drawings of the following dynamos: Brush arc-light machine, Plate XVI.; Mordey "Victoria" dynamo, Fig. 336, p. 499; Mordey alternator, Fig. 437; Ferranti alternator, Plate XXVI., Fig. 2. That of the Kapp alternator, Fig. 421, built by Messrs. Johnson and Phillips, is shown in Fig. 280.

Spherical Bearings.—With all long bearings it is of great importance that they should not only be exactly concentric, but that they should also be accurately in line. To permit the steps to adjust themselves to perfect allignment it is now a frequent practice to provide them with a spherical seat; that is to say a spherical or nearly spherical shape is given to the enlarged central portion of the bearings, and this spherical portion is provided with a soft-metal seat on the pedestal.[1] Fig. 281 gives a design by Mr. Ravenshaw used in Goolden & Co.'s dynamos. Messrs. Siemens employ a less satisfactory form of oval instead of spherical outline. The bearings of the Westinghouse alternator closely resemble Fig. 281, but are adapted to longer journals. The great alternators of Ferran Plate XXVI. Fig. 2, have thrust-bearings borne upon spheric seats. Ball bearings, resembling those employed in bicycle

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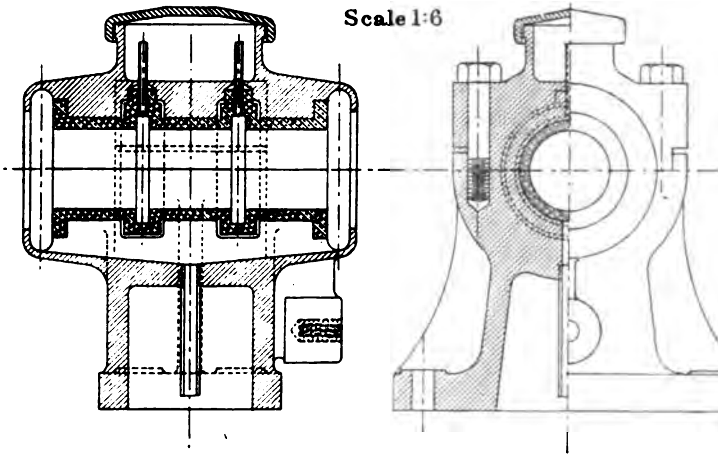
[1] See paper by Mr. Coleman Sellers, in *Journal of Franklin Institute* for 1872, or *Engineering*, xv. 17, or the figure in Unwin's *Machine Design*, p. 170.

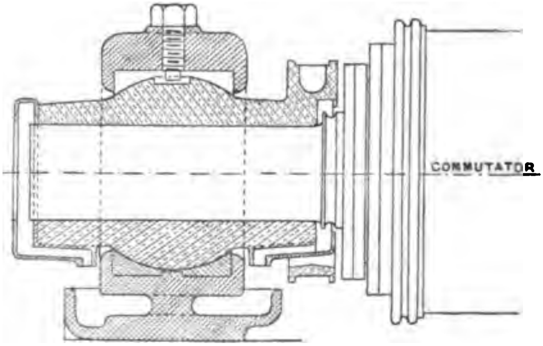
FIG. 280.



THRUST-BEARING OF KAPP ALTERNATOR.

have been suggested by Reignier, and have also been tried the States.

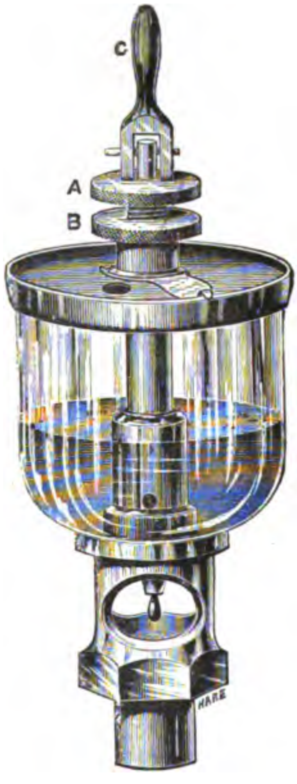
FIG. 281.



SPHERICAL BEARING OF GOOLDEN DYNAMO.

Lubricators.—Provision must be made for lubricatin bearings with a due supply of oil or grease, and arrangement to prevent waste and spilling. It is usual to provide an oil-well in the hollow casting of the pedestals, into which the oil drains from the ends of the brasses. Sight-feed lubricators which supply the oil visibly drop by drop are undoubtedly best for ordinary machines. Such a lubricator is illustrated in Fig. 282. The lever C at the top closes the feed of oil when the machine is not wanted to run. The collars A and B regulate the rate at which the oil flows down to drop through the tube-sight below. For ship dynamos special forms that cannot spill oil are preferable. It is usual to provide a collar on the journals to collect and throw off the oil centrifugally, the lips of the bearing being carried (as shown in Fig. 281, above) beyond the brasses, and provided with a re-entrant rim which catches the oil and returns it to the well below. For large dynamos, where there is great weight on the bearings, special precautions have to be taken, as in the lubrication of the bearings of propellor shafts. Oil is supplied under pressure, sometimes from two independent sources, to prevent risk of failure. Such arrangements are the more needful in the case of dynamos, because the motion is one of pure rotation, the shaft not being subjected, like the crank-shaft of a steam engine, to alternate lateral thrusts, which help to work the oil in under the journals. Sellers has proposed a double lubrication [1] as a safeguard. The ordinary

FIG. 282.



VISIBLE DROP-FEED LUBRICATOR.

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[1] Unwin's *Machine Design*, p. 171.

lubricator supplies oil at the centre of the bearing, a top brass is provided near each end with a cup co a stiff mixture of tallow and oil, which only melts the bearing heats from failure of the ordinary oil Self-lubricating devices are sometimes used, an oil-wel provided in the lower brass, into which dips a co the journal, or a metal ring running loosely over it, a mere ring of felt. (See Gramme dynamo, Fig. 325,

Keys and Feathers.—Keys for securing the armat pulley to the shaft should be of the sunk or flat type the saddle type, which is less reliable. The rules for k as follows: b meaning breadth ; t thickness ; and d d of the eye of the hub, all in inches—

$$b = \tfrac{1}{4} d + \tfrac{1}{8}'' ;$$
$$t\text{, for sunk keys} = \tfrac{1}{10} d + \tfrac{1}{8}'' ;$$
$$t\text{, for flat keys} = \tfrac{1}{11} d + \tfrac{1}{16}'' ;$$

Where two or more feathers are used on opposite sides shaft, the breadth of each may be somewhat less th For small machines these numbers are needlessly larg for less than 5 H.P. the formula on p. 390 may be us the constant c taken as 4 or 5.

Pulleys and Belts.—There is no need to give speci for these, as the ordinary rules for running machinery

Bed-plates.—In designing bed-plates it is usual t weight of metal by coring out and leaving stiffening r flanges. All this is quite right except in those case any part of the bed-plate serves also a magnetic purp constitutes a part of the magnetic circuit. For exa the Paterson & Cooper dynamo, Plate V., the be serves partially as a yoke for the field-magnet; and "Manchester" dynamo of Mather and Platt, Fig. 333, p. also in Brown's dynamo, Plate IV., the part of the castin passes under the armature must be left solid. An e of injurious hollowing occurs in Fig. 325, p. 483 (G 1884). It should also be noted that in the case of m with drum or cylindrical-ring armatures it is convenie able to withdraw the armature longitudinally by re one pedestal, which therefore should be a separate casting. In that case, for machines of the over-type, it is convenient that the pedestal should be made removable down to the level of the under side of the armature, so that when the upper part is removed the stump may form a convenient resting place for the armature in removal. A case is shown in Fig. 325, p. 484 (Gramme, 1884), and in the Kapp dynamo, Plate I.

Couplings.—When dynamos are driven without belting from a steam-engine on the same bed-plate, it is frequent to connect their respective shafts by a coupling. Of these devices there are several special patterns, such as Brotherhood's, with a connecting part of leather, and Raworth's with flexible steel bands, admitting of a certain amount of play if the two shafts are not in exact alignment. Willans has constructed an ingenious magnetic coupling-clutch.

The questions of the mechanical securing of armatures to shafts, and of the proper strength of binding wires, are discussed in Chapter XIII., on Armature Construction.

CHAPTER XVI.

ELEMENTS OF DYNAMO DESIGN : CALCULATIO
WINDINGS.

THE symbols used in this chapter are explained on

As in all designing of machines, so with the des dynamos, experience is the ultimate guide. To machine which, when driven at a prescribed speed, sh any desired number of amperes of current at a voltage, is a very simple matter to an engineer already had experience in designing dynamos of general type, but of different output. To a man designed two-pole continuous current machines fo descent lighting it is a simple matter to design another of the same sort. But it would be to him by no easy from this experience only to pass to designing of a multipolar type, or to design alternate-current m

It is known, for example, that the number of output of a dynamo of given form, at a given approximately proportional to its weight. For examp a dynamo which at 720 revolutions per minute yields sparking or overheating) 200 amperes at 105 vo known that using the same iron carcase, and rewi machine with new coils equal in weight to those p used, the machine may be made to give (at same before) 300 amperes at 70 volts, or 250 amperes at or 30 amperes at 700 volts—the product in each of th being 21,000 watts. A machine for double the outp have double the weight of iron and double the copper, approximately, if of the same type.

Also, since the voltage is proportional to speed, dynamo had to be designed to give the same out speed of 480 instead of 720 revolutions per minute, about 1½ times as heavy would be required. A manufacturer who had in stock carcases of various sizes would, of course, select the nearest size and wind it with an appropriate winding.

But to begin anew to design a dynamo without this kind of practical basis is a different matter. The first stage in understanding this is to examine carefully the design of some well-established machines, and to see how the dimensions of their several parts are adapted to their functions. It will then be an easier matter to work out any case for a fresh type of machine.

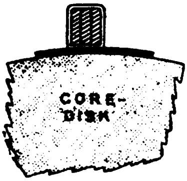
Calculations are needed to ascertain the proper sizes of the parts. Some of these calculations are purely electrical, others magnetic, others mechanical, and some are of a wholly empirical nature founded on experience. If a dynamo is to be constructed to give, say, an output of 200 amperes at 55 volts, the conditions respecting safety from overheating practically determine the size of wire that can be used for the prescribed current: no calculation being needed beyond a reference to such a Table as that in Appendix B, and the knowledge that in armatures of dynamos it is usually quite safe to allow 2000 or more amperes to the square inch. Suppose we settle on a stranded wire of 7 No. 13 S.W.G., which will safely carry 100 amperes (each conductor carries only *half* the armature current). But though this is simple, it is needful to remember that if the field-magnet is shunt-wound, as it must be for ordinary lighting at constant pressure, there will be additional amperes to allow for besides the 200 for the lamps. Let it be taken that 5 amperes, or 2½ per cent. of the current will suffice. Suppose this all settled, then the question arises of the 55 volts. What size of armature, what winding of it, what size of field-magnet will be required; and how must the latter be wound so as to give what is required at the proper speed? Again, it must be remembered that if 55 volts is to be the pressure at the mains, the armature must generate more volts than this—say 57 or 58—to allow a margin for the "lost" volts (p. 252). Suppose this settled, then what is the next step?

Consider the fundamental equation of the cc current dynamo (see pp. 47 and 210).

$$E = n \, C \, N \div 10^8.$$

Now if we assume that the speed n is prescribed bel this formula tells us that the volts of the armature d C, the number of armature conductors employed (i. weight of copper), and on N, the number of magn through the armature (i. e. on the cross-section of core, and on the degree to which its magnetization up). In the case in question suppose the prescribed be 1140 revolutions per minute, then n (the revolut second) = 19. And if E is taken at 57, it follows t multiplied together must come to exactly 300,000,0 how much must C and N be separately? Well, ex shows that in such machines as this is to be, each a section should consist of one, or, at most, tw whether wound as ring or as drum. Experience als that for 2-pole machines it is convenient if the nu sections (and therefore of bars in the commutat multiple of 6. Also experience shows that if there a sections than 30 there will be fluctuations and possib troubles, and that if there are so many as 150 or there comes in great expense in the construction. W take 42, or 48, or 54, or 60, or 72, and work out a de any of these. It is very easy, on completing the calc to try another set if the first do not seem quite sati If there is only one convolution in each section, armature is ring-wound, C will be the same as the nu bars of the commutator; but if drum-winding is adopt C will be numerically twice as great. Now if C is smal be large, and *vice versâ;* and we know that to secure s running it is well to keep N large and C small (p. 103) pose, then, we take C at 72, so that when wound dr there will be 36 sections and'a 36-bar commutator. Cle will involve that N shall equal 300,000,000 ÷ 72 = 4,1 in round numbers there must be a flux of 4,170,000 m lines through the core of the armature. Again, ex shows that the proper degree of magnetization to allow in armatures of such machines is (see p. 422) from 12,000 to 17,000 lines to the square centimetre, or say from about 70,000 to 100,000 lines to the square inch. To carry the 4,170,000 lines the armature core ought then to have a nett cross section of about 45 square inches, or, say, 288 square centimetres. But here again comes a choice. How shall we determine this cross-section? What size of core-disk shall we choose, and what total length of core-disks shall we pack together along the shaft? If we take large core-disks of great radial depth we shall only need a comparatively small number of them, and our armature will be short; whereas if we take small core-disks we shall have a long armature. Here two other considerations come in to influence our decision. We have provisionally settled the gauge of copper conductor to carry our current—a stranded wire of 7 No. 13's, of which 3·38 turns will lie side by side in the breadth of an inch. If there are to be 72 such conductors all in one layer, they will occupy about 21 inches side by side. If we allow nothing extra for inserting driving-horns, this will involve core-disks about 7 inches in external diameter. If we say 7¼ inches with a 4¼-inch hole, the doubled radial depth of iron will be 3 inches; and as there are to be 45 square inches of section of iron that will require a total length of about 15 inches, or, with the insulation between the core-disks a length of 16 inches, the core of the drum will then be about twice as long as its own diameter. It is usual in drum cores to make the length a little greater than the diameter; but this will do for present purposes. But there is another consideration. If we have got so many complete convolutions of conductor as 36, and each conductor carries 102½ amperes, there will be for total cross-magnetizing effect a product of 3690 ampere-turns. Will this, on the core-disk of 7¼ inches diameter be too great—that is to say, so great as to cause sparking? This is purely a question for experience to decide (see p. 436). Now experience shows that in 2-pole drum-wound machines a core-disk 7¼ inches in diameter will carry at least 5200 ampere turns without sparking, so that we are well within the limit of sparklessness. We might diminish internal resistances little by choosing a smaller core-disk, so as to make a long core that will waste less wire in wrapping across the end but in that case we cannot use the stranded wire first select If, for example, we chose 6-inch core-disks with 2-inch hol we should require a nett length of 12 inches, or a gross leng of nearly 13 inches. And we could not fit the seventy-t conductors around the periphery unless these were specia made, say of drawn copper strips placed three side by si (as in Fig. 283), each strip being in section 250 mils wide 60 mils thick. The three overspun toget would be about 210 mils thick ; and seventy-two would occupy about 15 inc around the periphery of the 6-inch di leaving 3·8 inch for the insertion of drivi horns. Another way of winding would to use, with 8½-inch core-disks, four wi in parallel, instead of the stranded c ductor, each wire being a No. 10 S.W. carrying 25 amperes, arranged two deep, there being around the periphery, and occupying about 22 inches side side. If the manufacturer had in stock no core-disks these sizes, but had some of 7-inch, he would probably these, and select a wire to suit. The difference in the fi efficiency of the machine would be trifling.

FIG. 283.



Assume then that as the result of all these considerati the 7¼-inch core-disks have been chosen, that the armat core is 15 inches long, and that the insulation and cop windings and binding wires will bring up the exter diameter to about 8⅛ inches—it now remains to design field-magnet.

We will settle upon the form of Fig. 121 as the type, a construct the horizontal limbs of cast iron. We must, p visionally at least, assume a value for the leakage coeffici which in this type is rather high, say 2·0. Hence we m design the field-magnet to carry 8,340,000 magnetic li instead of 4,170,000. And, as experience shows that it is well to force the magnetization beyond about 7000 lines the square centimetre or 43,000 to the square inch, this implies a cross-section of at least 194 square inches, or about 1191 square centimetres. Again, experience shows that it is well if the armature core extends a trifle beyond the field-magnet on each side. This can be attained by bevelling the edges of the polar parts while keeping the rest broad. Suppose the field-magnet limbs to be made 16½ inches wide from front to back, and 11½ inches in depth; then what length must they be? Obviously a sufficient length to leave room between them for the wrought-iron core and the bobbin large enough to hold the proper amount of winding necessary to excite the magnetization to the prescribed degree. To ascertain the amount of wire that is requisite one has first to calculate the number of ampere-turns by the principle of the magnetic circuit. But how can we apply the principle of the magnetic circuit without knowing the length of iron that is to be used? The method usually adopted here is one of approximation. Make a preliminary calculation in which a rough estimate is inserted for the yet undetermined length of the iron limbs. Having done this, see whether, without mechanical difficulty or risk of overheating, the quantity of wire thus calculated can be wound upon the length of limb so assumed; and having made this comparison, then diminish or increase the length chosen for the limb, and recalculate. But here again comes in a complexity. If we assume that the armature has no demagnetizing reaction, we shall find our calculated quantity of wire much below the quantity actually required. Therefore, calculate approximately by the rule given on p. 285 the number of demagnetizing ampere-turns, and add 2·0 times this to the number previously found; for the field-magnet must be made long enough to carry this additional number of coils. In the case under consideration assume the polar angle to be 145° on each side, it follows that $\frac{145}{180}$ of 72, or about 58 of the conductors of the armature will be in the gap-spaces at any one moment, and that there will be a belt of conductors (see Fig. 71, p. 90), seven broad, exposed between the tips of the poles. This gives us 700

ampere-turns of demagnetizing power if the bru
assumed to be set near the pole-tips.

Now the external diameter of the armature is 8
and we must allow ⅛ inch clearance all round, m
diameter of the bored polar surface 8¼ inches, and t
gap-space from iron to iron ½ inch. The gap-spac
selves may be taken as being 10¾ inches along the c
15 inches from back to front. We are now read
rules by which to calculate the field-magnet design
we may pause here in these general considerations, w
been followed far enough to show the need for hand
of sufficient exactness.

ELECTRICAL CALCULATIONS.

§ 1. *To Calculate the Lost Volts in the Armature.*—Me
an amperemeter the number of amperes i_a flowing th
armature; multiply this by the number of ohms (or frac
ohm) that represents the internal resistance of the armatur

$$\text{Lost volts} = r_a \times i_a$$

A similar mode is to be used for calculating the vo
resistance in any coil in series with the armature. If
internal main-circuit resistances, such as a series coil, ar
we must add this to r_a and get

$$\text{Lost volts} = (r_a + r_m) \times i_a.$$

§ 2. *To Calculate the Current going through Shunt.*—D
e at terminals by number of ohms of resistance r_s of shunt

$$i_s = e \div r_s$$

In a good modern machine i_s may be taken as about 3
(or less) of *i*.

§ 3. *To Calculate the Whole Current flowing through A*
Add to the number of amperes *i* that flow to the lamps, t
of amperes i_s flowing around the shunt coil.

$$i_a = i + i_s$$

Or about 3 per cent. may be added to the current s
the mains.

§ 4. *To find the Gauge of Wire needful for the Armature.*—Remembering that there are two paths through the armature, divide i_a by 2, and then refer to the *Amperage and Wire-Gauge Table*, Appendix B, and select a wire. Remember that in very small machines it is safe to go up to 4000 amperes per square inch, and in large machines to 2000 amperes per square inch.

§ 5. *To find the Whole Electromotive-force Generated in the Armature of a Dynamo.*—Ascertain the number of volts of pressure e, at which the mains are to be supplied from the terminals of the dynamo (depending on the lamps that are to be used): to this add the calculated number of *lost volts.*

$$E = e + r_a i_a$$

Then E is the volts which the armature must generate.

§ 6. *To calculate the number of Armature Conductors* C.—This is a matter of experience: see pp. 374 and 400.

§ 7. *To Calculate the Electromotive-force in the Armature. (Continuous Current Machines.)*—Multiply together the revolutions per second n, the number of armature conductors C, and the magnetic flux N, then divide by one hundred million. For:—

1 volt = the cutting of 100,000,000 magnetic lines per second;
or

1 volt = 10^8 C.G.S. units of electromotive-force.

$$E \text{ (volts)} = \frac{n \, C \, N}{10^8}$$

[Example: a certain Phœnix dynamo. $n = 23{\cdot}6$; $C = 180$; $N = 2{,}606{,}000$. Find E.]

EFFICIENCY CALCULATIONS.

§ 8. *To Calculate the Wasted Power in a Dynamo.*—N.B.—To calculate horse-power from the watts divide the number of watts by 746.

(1) Watts wasted in armature coil. Multiply volts lost in armature by amperes in armature: or multiply resistance of armature by square of armature current.

(2) Watts wasted in series coil. Multiply volts lost in series coil by amperes in that coil: or multiply resistance of coil by square of amperes in that coil.

(3) Watts wasted in shunt coil. Multiply amperes in s volts at terminals of shunt: or divide square of volts at tern resistance of shunt coil.

(4) Watts wasted by eddy currents not calculable directl

(5) Watts wasted by magnetic hysteresis. The figures p. 163 state the number of watts wasted by hysteresis laminated soft-wrought iron, when subjected to a succe cycles of magnetization as in the rotating armature co dynamo.

§ 9. *To Calculate the Electrical Efficiency.*—Multiply toge useful current i and available volts e, and so obtain the use Multiply together the total current i_a and total electromotive and so obtain the total watts of gross output. The efficiency is the ratio of the former to the latter.

$$\eta = e\,i \div \mathrm{E}\,i_a.$$

Or it may be calculated by dividing the useful watts by watts (useful and wasted added together). The electrical does not include waste by eddy-currents, hysteresis, or fricti

§ 10. *To Ascertain the Commercial Efficiency.*—This branch of designing but belongs to testing. See Chapter X

MAGNETIC CALCULATIONS.

§ 11. *To Calculate the Magnetic Flux through the Ar* Measure e, add lost volts, and so calculate E, then mu 10^8 and divide by n and by C.

$$\mathrm{N} = \frac{\mathrm{E} \times 10^8}{n \times \mathrm{C}}.$$

[Example: An Edison-Hopkinson dynamo. $n = 12{\cdot}5$; $e = 105$; $r_a\,i_a = 3{\cdot}26$; find N.]

§ 12. *To Calculate the Magnetic Induction.* B *in an Iro* Ascertain the magnetic flux N through that core; and cross-section A, of iron in that core. Then divide N by A.

$$\mathrm{B} = \mathrm{N} \div \mathrm{A};$$

or, if measures are given in square inches,

$$\mathrm{B}_{''} = \mathrm{N} \div \mathrm{A}''$$

[Example: in an Edison-Hopkinson dynamo N in armature = 10,826,000; $A'' = 125$ square inch; find $B_{''}$.]

[Example: in a Kapp dynamo N in armature = 6,730,000; $A = 403\cdot 1$ square centimetres; find B.]

§ 13. *To Calculate the Cross-Section of Iron to carry a given number of Magnetic Lines.*—First determine how many is the total number of magnetic lines that must pass through the armature core when machine is at full work: call this N. Next, settle what is the advisable value to give to the magnetic induction B. In continuous current machines for incandescent lighting it is not usually advisable to push the magnetization further than $B = 17{,}000$ (to the square centimetre), or $B_{''} = 110{,}000$ (to the square inch). For arc-lighting machines the magnetization may be pushed further. For alternate-current machines (and also for cores of transformers) a much lower degree of magnetization is desirable: say $B = 7{,}000$, or $B_{''} = 45{,}200$. Having settled the value of B or $B_{''}$, dividing N by the value settled will give the required sectional area A or A''.

[Example: in a certain Phœnix dynamo it was decided that $B_{''}$ should be 115,000 lines per square inch, and N had to be 2,606,000; find A''.]

[Example: in a Kapp alternator A in the armature core was $103\cdot 2$ square centimetres; assuming $B = 6500$; calculate N.]

[Example: in an Edison-Hopkinson dynamo N in armature = 10,826,000: $A'' = 125$ square inches; find $B_{''}$.]

For calculating the requisite cross-section of field-magnets a similar process is used, but allowance must be made, as explained later, for carrying a larger number of magnetic lines (because of magnetic leakage); and it is advisable to use, even with wrought-iron cores, a somewhat lower degree of magnetization. If cast-iron cores are used, the section will have to be nearly twice as great, as it is not advisable in that material to force in more than about 8,000 lines to the square centimetre, or than about 50,000 to the square inch.

§ 14. *To allow for Magnetic Leakage.*—In consequence of magnetic leakage the magnetic flux is different at different parts of the magnetic circuit.

[Example: in an Edison-Hopkinson dynamo it was found that to get 10,825,000 lines through the armature, enough magnetizing power had to be put on to make 14,289,000 lines flow through the field-magnet, 3,464,000 of these leaking away and not going through the armature. This is as if out of every 132 lines in field-magnet, 100 only were useful and 32 wasted.]

The symbol for the coefficient of allowance for leakage is v. Its value varies in different dynamos from 1·2 to 2 or more. In th example above given $v = 1{\cdot}32$. Allowance must be made for times N magnetic lines in the field-magnet in order that there sha be a flux of N lines through the armature. (Compare p. 183.)

§ 15. *To find the Permeability of Iron at any stage.*—The rat between the number of magnetic lines that there are in the iron (other material) and the number that there would have been (wit same magnetizing force) in air, is called the *permeability* of the iro Symbol μ.

The value of μ is = 1 in air, copper, and all non-magnet materials. In iron it varies with the quality of the metal, an with the degree of saturation to which the magnetization has bee pushed, getting smaller as the magnetization is pushed toward satura tion. It also differs in different specimens of the same brand of iro from same forge or foundry. Tables I. and II., p. 143, are deduce from data given by Hopkinson in Phil. Trans. of Royal Societ 1885, for two sorts of iron used by Mather and Platt in buildin Hopkinson's dynamos. The curves, and the values in terms o square centimetres are given on pp. 144 and 145 above.

Suppose B has been found from N and A as above, and it i desired to know what value μ will be at that stage of magnetization the designer must refer to the tables or to the curves and see wha value of μ corresponds to the value of B.

[Example: in armature of Kapp dynamo, when running on ope circuit $N = 6{,}730{,}000$; $A = 403{\cdot}1$ square centimetres; find B and from this, assuming iron is of same quality as in Table I. p. 14 find μ. Also find B and μ, when, at full load, N is increased up t 71,170,00 by the added magnetizing action of the series coil.]

[Example: in field-magnet (cast iron) of a Phœnix dynamo $A'' = 62$ square inches; N in armature = 2,606,000; v (leakage allowance coefficient) = 1·36. Calculate v N, then $B_{''}$; then find by reference to Table II., p. 146, for cast iron.]

CALCULATIONS RESPECTING MAGNETIC CIRCUIT.

Fundamental Law of Magnetic Circuit.

Magnetomotive-force ÷ magnetic reluctance = the magnetic flux; or, inversely, thus:—

§ 16. *To Calculate the Magnetomotive-force requisite to force a given number of Magnetic Lines through a Definite Magnetic Reluctance.*—Multiply the number which represents the magnetic reluctance by the number of magnetic lines that are to be forced through it. The product will be the amount of the magnetomotive-force.

If the magnetic reluctance has been expressed on the basis of centimetre measurements, the magnetomotive-force, calculated in this way, will require to be divided by 1·257 $\left(i.e. \text{ by } \frac{4\pi}{10}\right)$ to give the number of ampere-turns of requisite magnetizing power. If, however, the magnetic reluctance has been expressed in the units explained below, based upon inch measures, the magnetizing power, calculated by the rule given above, will already be expressed directly in ampere-turns.

§ 17. *To Calculate Magnetic Reluctance of an iron core.*

(*a*) *If dimensions are given in centimetres.*—Magnetic reluctance being directly proportional to length, and inversely proportional to sectional area, and to permeability, the following is the formula:

$$\text{Magnetic reluctance} = \frac{l}{A\,\mu};$$

but the value of μ cannot be inserted until it has been calculated from B as above in section 15.

(*b*) *If dimensions are given in inches.*—In this place we apply a numerical coefficient, which takes into account the change of units (2·54 centimetres to the inch), and also, at the same time includes the operation of dividing the magnetomotive-force by $\frac{4}{10}$ of π (= 1·257) to reduce it to ampere-turns. So the rule becomes:—Divide the length (in inches) by the area (in square inches), and by the permeability (formed as above from $B_{''}$), and then multiply by 0·3132. Or in symbols:—

$$\text{Magnetic reluctance} = \frac{l''}{A''\,\mu} \times 0·3132.$$

[Example: find the magnetic reluctance from end to end of a bar of wrought-iron 10 inches long, with a cross-section c inches, on the supposition that the magnetic flux (N) thr amount to 440,000 lines.]

§ 18. *To Calculate the Total Magnetic Reluctance of th Circuit of a Dynamo.*—This is done by calculating th reluctances of the separate parts and adding them togethe must, however, be taken of magnetic leakages, by allowi lines in the field-magnet cores and yoke.

In the simplest case the magnetic circuit consists of t (1) iron in armature core; (2) air, copper, cotton, & spaces; (3) iron in field-magnet. The permeability of th in the gap-spaces may be taken as = 1. Hence the t ances in question are respectively written :—

	For centimetre measure.	For inch measur
1. Armature	$\frac{l_1}{A_1 \mu_1}$	$\frac{l_1}{A''_1 \mu_1} \times 0{\cdot}31$
2. The Gap-spaces	$\frac{2l_2}{A_2 \mu_2}$	$\frac{2l_2}{A''_2 \mu_2} \times 0{\cdot}3$
3. Magnet core ..	$\frac{l_3}{A_3 \mu_3}$	$\frac{l''_3}{A''_3 \mu_3} \times 0{\cdot}3$

If the iron used in armature and field-magnet is of sa and if A_3 has been taken equal to v times A_1 so tha magnetized up to equal degree, μ_3 and μ_1 will be alike. gap-spaces $\mu = 1$.

If there were no leakage, the total reluctance would the sum of these three; but leakage reduces the total relu at the same time obliges us to increase N in the magnet fore to increase the ampere-turns.

§ 19. *To Calculate the Ampere-turns of Magnetizing Power Force the Desired Magnetic Flux through the Reluct Magnetic Circuit.*

(*a*) *If the dimensions have been given in centimetres*, the

Ampere-turns = magnetic flux multiplied by the magnetic
divided by $\frac{4}{10}$ of π (= 1·257);

or, in detail, the three separate amounts of ampere-turns required for the three principal magnetic reluctances of a dynamo are expressed as follow :—

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \text{N lines through iron of armature}\end{array}\right\} = \mathrm{N} \times \frac{l_1}{A_1\,\mu_1} \div \frac{4\pi}{10};$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \text{N lines through the two gap spaces}\end{array}\right\} = \mathrm{N} \times \frac{2\,l_2}{A_2} \div \frac{4\pi}{10};$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ v\,\text{N lines through the iron of}\\ \text{field-magnet}\end{array}\right\} = v\mathrm{N} \times \frac{l_3}{A_3\,\mu_3} \div \frac{4\pi}{10}$$

and, adding up :

$$\text{Total ampere-turns required} = \frac{10}{4\pi}\mathrm{N}\left\{\frac{l_1}{A_1\,\mu_1} + \frac{2l_2}{A_2} + \frac{vl}{A_3\,\mu_3}\right\}$$

(*b*) *If the dimensions are given in inches*, the rule is :—

Ampere-turns = magnetic flux multiplied by magnetic reluctance ;

or; in detail :

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \text{N lines through iron of}\\ \text{armature}\end{array}\right\} = \mathrm{N} \times \frac{l''_1}{A''_1\,\mu_1} \times 0{\cdot}3132;$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \text{N lines through two gap-}\\ \text{spaces}\end{array}\right\} = \mathrm{N} \times \frac{2l''_2}{A''_2} \times 0{\cdot}3132;$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ v\,\text{N lines through iron of}\\ \text{field-magnets}\end{array}\right\} = v\mathrm{N} \times \frac{l''_3}{A''_3\,\mu_3} \times 0{\cdot}3132.$$

and, adding up :

$$\left.\begin{array}{l}\text{Total ampere-turns}\\ \text{required}\end{array}\right\} = 0{\cdot}3132\,\mathrm{N}\left\{\frac{l''_1}{A''_1\,\mu_1} + \frac{2l''_2}{A''_2} + \frac{vl}{A''_3\,\mu_3}\right\}$$

[Example: in a certain Lahmeyer dynamo, with cast-iron magnets, the following were the data: $\mathrm{N} = 2{,}328{,}000$; $v = 1{\cdot}11$; $l''_1 = 6\frac{9}{32}$; $l''_2 = \frac{13}{64}$; $l''_3 = 40$; $A''_1 = 34{\cdot}8$ sq. in. ; $A''_2 = 69{\cdot}5$; $A''_3 = 86{\cdot}5$; calculate the required ampere-turns.]

In some forms of dynamo the magnetic reluctances of pole-pieces and yokes must be separately calculated; and allowance must in

some cases be made for leakages at different parts of t
Hence a more careful formula would be :—

$$Si = 0\cdot3132\ N \left\{ \frac{l''_1}{A_1\ \mu_1} + \frac{2l''_2}{A_2} + \frac{v_3\ l''_3}{A_3\ \mu_3} + \frac{v_4\ l''_4}{A_4\ \mu_4} + \frac{v}{A}\right.$$

It is expedient that the calculation of the ampere-turns
made *twice;* that is once (using the value of N that corr
the case of no lost volts) to find the value of the ampe
winding to be put on the shunt, when there is no current t
lamps; and once (using the higher value of N that corr
the maximum E) to find the increased ampere-turns that a
when the full current is being taken from the armature.
have to be provided for (in compound-wound machines)
coil, which also will need to have additional windings to c
for demagnetizing effect of armature.

§ 20. *To Estimate the Additional Ampere-turns Required to*
for the Demagnetizing Action of the Armature Curren
Brushes have a Forward Lead.

Count the number of conductors on periphery, be
diameter of symmetry and the actual diameter of commu
multiply by i_a the amperes flowing through armature. (App
half the number of conductors exposed in one of the spac
the corners of the two pole-pieces may be taken for m
The product so found should be multiplied by v, and t
to the number of ampere-turns found as in the last
For ring machines the product must be doubled. Arnoux
the number is in ring machines about 15 per cent. of the shu
terms; whilst in drum machines it varies from 5 to 7 per

EXAMPLES OF CALCULATIONS APPLIED TO CON
CURRENT DYNAMOS.

As remarked at the opening of the present cha
advantageous to go over the calculation of some
machines. Two complete examples are given
relating to an Edison-Hopkinson dynamo (see pp.
and 520); the second to a Phœnix dynamo, Plate
magnetic-circuit calculations for the first have been

out in C.G.S. units; those in the second and third in inch units, so as to show both modes of calculation. As a third example, an exercise for calculation is given.

EXAMPLE I.—AN EDISON-HOPKINSON DYNAMO.

Description adapted from paper by J. and E. Hopkinson, in *Phil. Trans.*, 1886.

Shunt-Wound Dynamo, with Drum Armature: 33 kilowatts Output: 320 Amperes, at 105 volts, at 750 revolutions per minute.

Armature: Built up of about 1,000 iron core-plates stamped out of soft sheet iron separated by sheets of paper, and held between two end-plates, one of which is secured by a washer shrunk on to the shaft, and the other by a nut and a lock-nut screwed on shaft itself. Shaft of Bessemer steel, insulated before core-plates are threaded on.

Core-disks external diam.	$9\frac{5}{8}$	inch.	24·5	centim.
„ internal diam.	3	„	7·62	„
Shaft diam.	$2\frac{3}{4}$	„	6·985	„
Radial depth of iron	$3\frac{5}{16}$	„	8·45	,
Gross length of core	20	„	50·8	„
Total thickness paper insulation...	$1\frac{3}{8}$	„	3·4	„
Nett length of iron in core	$18\frac{5}{8}$	„	47·4	„
Nett cross section of iron	$123\frac{5}{16}$	sq.in.	801	sq. cm.
Ditto allowing for shaft	125	„	810	„

Core is wound with 40 convolutions (*i.e.* there are 80 external conductors at periphery) each consisting of 16 strands of copper wire 69 mils or 1·753 millimetres in diameter (*i.e.* $15\frac{1}{2}$ B. W. G.) the convolutions being placed in two layers of 20 each. Commutator 40 bars of copper insulated with mica; connections to armature so made that plane of commutation is horizontal when circuit is open. Cross section of the above wire, 0·0037 sq. in. or 2·3 sq. mm.; total ditto of each set of 16 wires 0·0592 sq. in., or 38 sq. mm. Resistance of armature from brush to brush 0·009947 ohm, at 13·5° Centigrade.

Field Magnet: Three forgings of hammered scrap iron, truly faced, and bolted together; section of limbs rectangular with

corners slightly rounded. Stands on a zinc footstep, over
bed-plate.

	Inch.	
Length of magnet limb	18	
Breadth of limb (parallel to shaft)	$17\frac{1}{2}$	
Thickness of limb	$8\frac{11}{16}$	
Length of yoke	$24\frac{1}{4}$	
Breadth of yoke	19	
Depth of yoke	$9\frac{1}{4}$	
Distance between centres of limbs	15	
Diam. of bore of polar faces	$10\frac{13}{16}$	
Depth of pole-pieces	9	
Width of pole-piece at narrowest part	$8\frac{3}{8}$	
Breadth of pole-pieces (parallel to shaft)	19	
Width of gap between pole-pieces	5	
Depth of edges of protruding horns	$\frac{5}{16}$	
Thickness of gap-space (from iron to iron)	$\frac{19}{32}$	
Thickness of zinc footstep	5	
Angular breadth of polar face		129°
Angular breadth of gap		51°

The magnetizing coils are wound directly on the
consist of 11 layers on each limb of copper wire 0·1
2·413 mm. diameter (No. 13 B. W. G.), having, ther
section of 0·0071 sq. in. or 4·573 sq. mm., making 3,2
tions in all; total length being approximately 15,0
4,570 metres. Resistance at 13·5° C. is 16·93 ohms.

Data for Calculating Reluctances in Magnetic Ci

1.—*Armature Core.*

l_1 taken as $5\frac{1}{8}$ inch or 13 cm.

A_1 taken as 125 sq. in. or 810 sq. cm.

2.—*Gap Space.*

l_2 is $\frac{19}{32}$ inch (= 0·59 inch), or 1·5 cm.

A_2 taken as 248 sq. in. or 1,600 sq. cm. This
sq. inch, or 190 sq. cm. for fringing. The ac
the polar face is $234\frac{1}{2}$ sq. inch, or 1,513 sq. c
corresponding area of 129° of surface of arma
$218\frac{1}{2}$ sq. inch, or 1,410 sq. cm. Allow, fo
margin all round equal to four-fifths of gap spa

3.—*Magnet Limbs.*

l_3 is in total 36 inch, or 91·4 cm.

A_3 is taken at 152 sq. inch, or 980 sq. cm.

4.—*Yoke.*

l_4 is taken at 19¼ inch, 49 cm., estimated along quadrants.

A_4 is 173½ sq. inch, or 1,120 sq. cm.

5.—*Pole Pieces.*

l_5 is $4\frac{5}{16}$ inch. or 11 cm., estimated along curve.

A_5 is taken as 190½ sq. inch or 1,230 sq. cm.; being mean area between section of limb and area of polar face.

Coefficient of leakage v was taken by Hopkinson as 1·32, but was probably nearer 1·4.

CALCULATIONS ABOUT THIS DYNAMO.

$i = 320$; $e = 105$; $n = \frac{750}{60} = 12{\cdot}5$; $r_a = 0{\cdot}01$; $r_s = 16{\cdot}93$, whence $i_s = e \div r_s = 6{\cdot}21$; $i_a = i + i_s = 326$; lost volts $= r_a \times i_a = 0{\cdot}01 \times 326 = 3{\cdot}26$; hence $E = e + r_a\, i_a = 108{\cdot}26$ at full load. $C = 80$.

$$N = \frac{E \times 100{,}000{,}000}{n\,C} = \frac{108{\cdot}26 \times 10}{12{\cdot}5 \times 80} = 10{,}826{,}000.$$

Useful watts $= e \times i = 105 \times 320 = 33{,}600$.

Total watts $= E \times i_a = 108{\cdot}26 \times 326 = 35{,}293$.

Electrical efficiency η = useful watts ÷ total watts.

" " = 0·952, or 95·2 per cent.

Watts lost in armature = lost volts × amperes;

" " " " $= 3{\cdot}26 \times 326 = 1{,}062{\cdot}76$.

Watts lost in magnets = lost amperes × volts.

" " " " $= 6 \times 105 = 630$.

Watts lost by hysteresis = 12·5 reversals per sec. in 2·83 cubic feet at 13,360 for B, see p. 163.

" " " " = 863.

To find ampere-turns requisite to magnetize. By § 19 above;

$$Si = \frac{10}{4\pi} \times 10{,}826{,}000 \times \text{the total magnetic reluctance.}$$

This must be calculated from the 5 data of the magnetic circuit in separate parts, as on p. 410. First find values of B in separate parts according to leakage and cross-section, and from these values find corresponding values of μ by Table I., p. 143.

1. Armature ... ... $B_1 = 13{,}360$; $\mu_1 = 1{,}000$
3. Magnet limbs ... $B_3 = 14{\cdot}250$; $\mu_3 = 796$
4. Yoke... ... ... $B_4 = 13{,}530$; $\mu_4 = 895$
5. Pole-pieces ... $B_5 = 11{,}450$; $\mu_5 = 1{,}566$

Inserting these values and those of the leakage coe
magnetic reluctances come out :—

1. Armature	0·000016
2. Gap-spaces	0·001875
3. Magnet limbs	0·000154
4. Yoke	0·000068
5. Pole-pieces	0·000001
Total Magnetic reluctance	0·002115

Whence

$$S i = \frac{10}{4\pi} \times 10{,}826{,}000 \times 0{\cdot}00211568$$
$$= 18226.$$

To this must be added the ampere-turns needed to com
demagnetizing action of armature. The number of arr
ductors between pole-tips is 11; but as the diameter of c
is not quite at the pole-tips we take 9 as the demagn
Multip'ying this by half the armature current (163 ampe
the leakage-coefficient (1·32) we get 19,36 as the co
number, making total requisite ampere-turns 20,162. I
by the number of amperes of current allowed in the shun
gives 3214 as the requisite number of coils on the f
The actual number wound on was 3260, which allows a
regulating.

EXAMPLE II ; A PHŒNIX DYNAMO (OVER-TYPE

DESCRIPTION : Compound-wound Dynamo with Rin
9 to 10 kilowatts, see Plate V. Figs. 1 and 2.

Output: 90 amperes at 105 volts, at 1,420 revo
minute.

ARMATURE : built up of about 225 iron core-plates (s
of soft sheet iron) separated by sheets of paper and held b
fixed firmly, but with due regard to insulation, througl
of four-armed spiders keyed to shaft.

Shaft of Bessemer steel.

Core-disks external diameter	$10\frac{5}{8}$ inch	26·99 c
,, ,, internal ,,	8 ,,	20·32
Shaft diameter	$1\frac{3}{4}$,,	4·45
Radial depth of iron	$1\frac{5}{16}$,,	3·33
Gross length of core	9 ,,	22·86 ,
Total thickness paper insulation	$\frac{11}{16}$,,	1·12 ,

Nett length of iron in core ... $8\frac{5}{16}$ inch or 20·11 cm.
Nett section of iron ... ... 22 sq. inch 141·9 sq. cms.
Thickness of core-disks No. 20, B.W.G. = 0·035 inch.

Core is wound with 36 windings each consisting of 5 convolutions of square copper wire 0·150 in. sq. or 3·81 mm. sq.; the convolutions being placed in one layer. No. of conductors on periphery is 180; commutator 36 bars of cast copper, insulated with mica. Cross section of above wire is 0·0225 sq. in. or about 14·5 sq. mms.

Resistance of armature from brush to brush 0·04 ohms.

Field-magnets: 2 castings, truly faced and bolted together: section of limbs rectangular with corners slightly rounded. The two limbs and a thin connecting-piece are cast in one; the bed-plate which also serves as yoke being a separate piece.

Length of magnet limb	$8\frac{3}{4}$	in. or	22·22	cm.
Breadth of limb (parallel to shaft) ...	9	"	22·86	"
Thickness of limb	7	"	17·78	"
Length of yoke	$21\frac{1}{2}$	"	54·61	"
Breadth of yoke	9	"	22·86	"
Depth of yoke	6	"	15·24	"
Distance between centres of limbs ...	$13\frac{1}{2}$	"	34·29	"
Diam. of bore of polar faces	$11\frac{3}{8}$	"	28·89	"
Depth of pole pieces	$9\frac{1}{2}$	"	24·13	"
Breadth of pole pieces (parallel to shaft)	9	"	22·86	"
Width of gap between pole pieces ...	$6\frac{1}{2}$	"	16·51	"
Thickness of gap-space (iron to iron)	$\frac{3}{8}$	"	0·95	"
Angular breadth of polar face		112°		
Angular breadth of gap		68°		

The magnetizing coils consist of a shunt as well as a series winding on each coil, and are wound on rectangular bobbins which are afterwards slid on to the limbs.

The series winding consists of 54 turns of copper wire (0·203 inch or 5·156 mm. diam.) No. 6 B.W.G. on each coil, having a cross section of ·032 sq. inch, or 10·645 sq. mm. Resistance of the series winding is ·021 ohms. Approximate length of series coils is 51 yards, or 46 metres. The shunt winding consists of 1727 turns on each coil (in all 3,454 turns) of copper wire 0·057 inch or 1·445 mm. diam., having a cross section of ·00255 sq. inch or 1·645 sq. mm. Resistance of shunt winding is 39·76 ohms. Length of shunt winding is approximately 1900 yards, or 1730 metres.

Ratio of inner to outer diameter of core is 7·53 to 10.
" radial depth of iron to extl. diam. of
core is ... ... 2·47 " 10.

Ratio of length of iron in core to diam. of core is ... ... 8·88 t

„ of depth of copper to depth of iron in core ... ... 1 ,

„ of depth of copper to external diam. of core 1

Data for calculating Reluctances of Magnetic Circuit

1. *Armature core:—*

l_1 taken as 6½ inch. or 16·51 cms.

A_1 taken as 21$\frac{13}{16}$ sq. inch, or 140·8 sq. cms.

μ_1 taken at 195.

2. *Gap-space:—*

l_2 is ⅜ inch, or ·95 cms.

A_2 taken as 127 sq. inch, or 820 sq. cms.

3. *Magnet-limbs:—*

l_3 is in total 17½ inch, or 44·4 cms.

A_3 is in total 62 sq. inch, or 340 sq. cms.

4. *Yoke:—*

l_4 taken as 12 inch, or 30·48 cms.

A_4 taken as 90 sq. in., or 580·5 sq. cms.

5. *Pole-pieces:—*

l_5 taken as 8$\frac{13}{16}$ inch, or 22·38 cms.

A_5 taken as 81 sq. inch, or 490 sq. cms., the m section of limb and polar surface.

Coefficient of leakage taken as 1·4.

Calculations about this dynamo:—

$i = 90$ amperes. $e = 105$ volts. $n = \frac{1420}{60} = 2$

$r_s = 39{\cdot}76$ ohms. $i_s = \dfrac{e}{r_s} = 2{\cdot}548$ amperes.

$i_a = i + i_s = 92{\cdot}548$ amperes.

$E = e + (r_a + r_m)\, i_a = 110{\cdot}7$.

N = 2,606,000, at full load; or 2,472,000 on oper

Useful watts $= e \times i$ $= 105 \times 90 = 9450$.

Total watts $= E \times i_a$ $= 110{\cdot}7 \times 92{\cdot}5 =$ 10,2

Electrical efficiency η = useful watts ÷ total w

„ „ = 92·3 per cent.

Watts lost in armature $= r_a\, i_a^2$.

„ „ = 342.

Watts lost in series coil $= r_m\, i_a^2$.

„ „ = 180.

Watts lost in shunt coil $= e\, i_s$.

„ „ = 265.

It will be noticed that in enumerating the dimensions selected for calculation, the nett length for the induction path through the armature has been taken at 6½ inches, or only equal to the width between the polar horns. The ring in this machine being very thin, the distribution of the magnetic flux through it is somewhat like that shown in Fig. 48, p. 63; the actual length of path along which the whole of the flux is confined to the mere radial depth of the core is actually less than the distance between the polar horns.

To find ampere-turns requisite to magnetize; apply rule of § 16, p. 409.

$$S i = N \times \text{total effective magnetic reluctance.}$$

The total effective reluctance (allowing for leakage) for the five separate terms is :—

$$\left\{\frac{6\frac{1}{2}}{21\frac{13}{16}\times\mu_1} + 2\frac{\frac{3}{8}}{127} + \frac{17\frac{1}{2}\times 1\cdot 4}{62\times\mu_3} + \frac{12\times 1\cdot 4}{90\times\mu_4} + \frac{8\frac{13}{16}}{81\times\mu_5}\right\} \times 0\cdot 3132.$$

The values of μ in the separate parts have to be found from tables such as those on p. 146, from the corresponding values of $B_{\prime\prime}$.

		$B_{\prime\prime}$	μ	Reluctance.	Ampere-turns needed.
Open Circuit.	1. Armature ..	113,200	195	0·000484	1196
	2. Gap-spaces ..	24,720	1	0·001885	4660
	3. Magnet Limbs	49,360	140	0·000901	2227
	4. Yoke	32,000	425	0·000141	349
	5. Pole-pieces ..	37,700	291	0·000121	299
			Total	0·003532	8731
Full Load.	1. Armature ..	119,300	75	0·001260	3115
	2. Gap-spaces ..	26,060	1	0·001885	4660
	3. Magnet Limbs	58,500	80	0·001576	3896
	4. Yoke	40,530	240	0·000248	615
	5. Pole-pieces ..	45,040	190	0·000185	457
			Total	0·005154	12741

As the shunt winding alone acts when the machine is on open circuit, it must provide 8731 ampere-turns; and the series winding at full load must not only provide the additional 4010 to 12,741 as shown above, to compensate for lost v increasing saturation, but must also provide additional compensate for demagnetizing effects.

Actual excitation of this dynamo was:—

Ampere-turns.	
8800	on open circuit.
2250	added by series winding to compe volts due to resistance assuming di meability.
2550	added by series winding to com magnetising effect of armature and due to lead of brushes.
13,600 =	total actual excitation at full load.

At 1,420 revolutions per minute machine gives out :-

Amp.	0	32	42	67·5	79·5
Volts.	103	104	105	105·2	105·2

Example III. (already partly considered on pp. 399

Design of a single-field compound-wound dynam armature. Output 200 amperes at 55 volts at 1140 re minute. It is required to find the appropriate field-mag

Armature.—Built up of core-disks, separated manilla paper fixed by end-clamping upon a three-web gun-metal. Shaft of Siemens steel. Commutator 36 ductors 72 all round periphery, in one layer. Hence a must be about 4,170,000 lines ; and at 90,000 lines to sq needs a nett cross-section of 45 square inches in core. 7¼ inches exterior diameter, 4¼ inches interior diamete numbers to make up total nett length of 15 inches are 28 mils (*i.e.* No. 22 S.W.G.) thick, so that about are needed. Conductor, a stranded wire of 7 No. together with double cotton covering, and already lig with Scott's rubber varnish. Resistance of armature f brush 0·007 ohms.; length of armature winding, a 52 yards.

Field-magnets.—Horizontal limbs of best cast i annealed, lower one forming part of bed-plate casting. Section widening from lips so as to have section 194 square inches, and at parts furthest from armature 16½ inches wide by 11 inches deep, being bored out to receive the ends of the wrought-iron magnet core, which is a round forging, 10½ inches diameter, turned down at its ends to 10 inches diameter, where it is inserted into the horizontal pole-pieces. The finished machine generally resembles Fig. 359, page 531. but is more massive in the field-magnets.

To find the proper length for this core make first an approximate estimate of the needed number of ampere-turns, and thence calculate the quantity of windings and the proper length of core to receive the wire. Then design the magnetic circuit to be as compact as possible; and having so settled the sizes of the parts calculate more exactly, as in the preceding example, the requisite number of ampere-turns to be provided on open circuit and at full load.

USEFUL POINTS. IN DESIGNING.

Peripheral Speeds.—The usual peripheral speeds appear to be from 2700 to 3000 feet per minute (*i.e.* 12 to 15 meters per second) for drums and cylindrical rings. Esson maintains that 6000 feet per second can be safely attained in large machines. For discoidal rings and disk armatures, 3000 to 5000 feet per minute is usual. Ferranti's 15 foot armatures (Plate XXVI., Fig. 2) have peripheral speed of 5400 ft. per sec. Those alternators in which the field-magnet revolves may have higher peripheral speeds without risk of flying to pieces, some going over 7000 feet per minute.

Core-disks.—These are usually from 25 to 50 mils in thickness, whether for ring or drum cores.

For rings, the ratio used in practice between the external and internal diameters is from 10 to 8 in small rings to 10 to 7 in large rings. In Brown's four-pole rings (Plate VIII.), the ratio is 10 to 7; in his eight-pole rings (Plate X.) about 10 to 8. In Siemens' machines with internal magnets (Plate XI.), the ratio is about 10 to 9. In machines with cast-iron magnets, the rings are usually made with a less radial depth of iron than in machines of wrought iron.

For drums, the usual ratio of external and internal diameters is 10 to 3. In Kapp's two-pole machine the ratio is 7 to 4.

Limit of Magnetization.—The limiting values to found expedient in practice to push the magneti been several times alluded to. The values of tabulated for convenience.

B = Lines per sq. cm.			
Species of Dynamo.	**In Armature.**	**In Gap Space.**	**In Fi**
			Wroug Iron
Constant Potential Machines.			
2-Pole Drum.	10,000 to 15,000	4,000 to 7,500	12,00 17,0
2-Pole Ring (long)	12,000 to 16,000	2,500 to 5,000	12,00 17,0
Multipolar Rings.	10,000 to 15,000	3,000 to 5,000	12,00 17,0
Arc-Light Machines.	17,000 to 20,000	3,000 to 7,000	17,00 20,0
Alternators.			
Multipolar Ring.	6,000 to 6,500	2,500 to 4,000	12,00 17,0
,, Drum.	6,000 to 7,000	2,500 to 5,000	12,00 17,0
Coreless Disk.	5,000	5,000	12,0

Size of Wire for Winding Armatures.—This wil discussed under heading of permissible heating. here remarked that modern practice allows from 2 amperes per square inch, in conductors of ring arm even up to 4000 amperes per square inch in thos armatures. But in the magnet coils, only about 20 per square inch. Esson[1] has given the followi usual sizes of wire (double cotton-covered and used in winding armatures to run at usual spee with the number of layers of each that may be used for these currents without overheating.

---

[1] *Electrical Review*, xxvii. 546, 1891.

Amperes to be carried.	Diameter of bare wire, in mils.	Number of layers.
5	48	4
7·5	62	3
10	75	3
20	90	2
22·5	2 × 75	2
25	3 × 65	3
32·5	2 × 80	2
37·5	126	1
40	2 × 90	2
50	2 × 109	2
50	148	1
60	180	1
75	203	1
90	238	1

The length of wire to produce a given voltage at a given speed is a measure (inversely) of the density of the magnetic field. The following are examples of 2-pole drum-wound dynamos. Edison-Hopkinson, at 750 revs. per min. takes 19 inches per volt. Kapp, at 780 revs. per min., takes 35 inches per volt. Thomson-Houston arc lighter, at 900 revs. per min. takes 148 inches per volt.

Heating of Magnet Coils.—All field-magnet coils are liable to heat, because even the purest copper offers resistance. If it be assumed that the thickness of the insulation is proportional to the thickness of the wire on which it is wound, it follows that the weight of copper in a coil filling a bobbin of given dimensions will be the same, whether a thick wire or a thin one be employed. Further, for a given volume to be filled with coils, the number of *ohms* of resistance of the coil will vary *directly as the square of the number of turns* in the coil. For if a coil wound with 100 turns of a given gauge be rewound with 200 turns of a wire having half the sectional area, the resistance of this new win obviously be four times as great as that of the origi ing. Also, by a similar argument, it follows that the of a coil of given volume will vary *inversely as the the sectional area* of the wire used. And as this ar portional to the square of the diameter of the wire, that the resistance is *inversely proportional to the fou of the diameter* of the wire used. (See also p. 430.)

The amount of heat developed per second in a product of the resistance into the square of the st the current. To avoid waste, therefore, no unnecess ance should be introduced into any main-circuit c easy to show that with a coil of *given volume*, the h is the same for the same magnetizing power, n whether the coil consists of few windings of thic many windings of thin wire. The heat per second is the magnetizing power is S i; i being the current, r ance, and S the number of turns. But r varies as t of S, if the volume occupied by the coils is constant. pose we double the number of coils, and halve t sectional area of the wire, each foot of the thinner offer twice as much resistance as before; and there as many feet of wire. The resistance is quadrupl fore. The heat is then proportional to $i^2 S^2$: and the heat is proportional to the square of the ma power. If, therefore, we apply the same magnetizi by means of the coil, the heat waste is the same, ho coil is wound. To magnetize the field-magnets of to the same degree of intensity requires the same ex of electric energy, whether they are series wound wound, provided the volume is the same. But if t of the coil (and the weight of copper in it) may be then the heat-waste may be proportionally lesse example, suppose a shunt coil of resistance r has Z we wind on another Z turns in addition, the ma power will remain nearly the same, though the curre cut down to one-half owing to the doubling of the re and the heat loss will be halved, for $2r \times (\frac{1}{2}i)^2$ will

In fact one ought to wind on so much copper wire that the annual interest on the prime cost is approximately equal to the annual cost of the electric energy spent in the inevitable heating.

It is assumed in the foregoing argument that we get double the number of turns on if we halve the sectional area of the copper wire. This is not quite true, because the thickness of the insulating covering bears a greater ratio to the diameter of the wire for wires of small gauge than for wires of large gauge. In designing dynamos, moreover, one ought to be guided by the question of economy, not by the accident of there being only a certain volume left for winding. If there is insufficient space round the cores to wind on the amount of wire that economy dictates, new cores should be prepared having a sufficient length to receive the wire which is economically appropriate.

If no special limit of temperature-rise is prescribed, then the dominant consideration that governs the selection of the wire for winding is the amount of energy that may be wasted in magnetizing. If a temperature-limit is prescribed, then there must be provided a cooling-surface proportional to the energy that is wasted in the magnetizing coil. Experience shows that if the heating is not to exceed 20° to 25° (Cent.) above atmospheric temperature, at least 2½ square inches of external surface of coil must be allowed for each watt wasted by the coil's resistance. Or, conversely, if a bobbin has room for a coil of only a certain amount of surface, a winding must be chosen such that it will waste only one watt for each 2½ square inches of surface. Some useful rules have been given by Kapp[1] for preliminary calculations about depth of winding and weight of wire. Of course, these might be determined by first calculating the gauge of wire, bare and insulated, number of turns, turns per layer, and resistance per turn. If l is the length of wire, and D is the depth of winding, both in inches, and X the excitation in ampere-turns, P the perimeter in inches of the coil, and W the weight of the coil in pounds, we have:

$$X = a\,l\sqrt{D}; \qquad [i.]$$

---

[1] See *Engineer*, April 1890.

where *a* is a coefficient which depends on the gau and thickness of its insulation. Also

$$W = \beta \frac{P}{l}\sqrt{\frac{X}{1000}};$$

where β is a second coefficient varying with the gau These two formulæ are applicable to the case temperature-limit being imposed we allow 2½ squ per watt. If no such limit is imposed and a give ture of energy is assumed, it is more convenient them by the following formulæ:

$$X = \gamma\sqrt{W\,l\,D \div P};$$

$$W = \delta\,\frac{P^2\,X^2}{1000000\,W}.$$

The four numerical coefficients then have the values :—

Diam. of Bare Wire in mils.	S.W.G.	α .	β	γ
40	19	522	0·495	820
120	10½	542	0·520	850
200	5½	570	0·615	900

For shunt coils the length, and therefore the dictated solely by reasons of economy. It is usu 25 to 30 yards per volt.

Permissible Heating, and Surface of Emission.- that any coil may not over-heat it must have surface, relatively to the amount of heat develope the current. The Brush arc dynamo, 2 sq. inches per watt lost, are allowed in the field-magnets, a inches in the armatures. In the Thomson-Housto 1·66 sq. inches. The relation between the heat de surface of emission, and the resulting rise of temp been investigated by Forbes, Esson, and other reckoned that heat would be emitted at the rate watt[1] from 1 square centimetre if warmed 1° C. above the surrounding atmosphere. Esson, on the other hand, finds that for surfaces consisting of wire double cotton-covered and varnished the emission is much more rapid; and gives $\frac{1}{355}$ of a watt as the rate of emission per sq. cm. per degree (Cent.). Within the range of ordinary heating it may be assumed that the rate of emission is proportional to the excess of temperature over the surrounding air. The difference between Esson's rule and Forbes's is that Esson allows for the aid to cooling afforded by the brass bobbins and iron cores; whilst Forbes deals with heat emitted from the coil-surface only.

Esson's rule, which appears to agree with the experience of various different makers, may then be stated

$$\theta^\circ \text{C.} = 355\,\frac{w}{s}\,;$$

where θ stands for the rise of temperature, w is the watts expended in heat in the coil, and s its surface in sq. cms. Or, if Fahrenheit degrees and sq. inches are used, the rule becomes

$$\theta^\circ \text{F.} = 100\,\frac{w}{s}.$$

In using such rules, and calculating the watts developed in the coil (by multiplying the resistance by the square of the current), it must be remembered that the wire when warm has a higher resistance than when cold. A useful rule to take this into account is :—

To find resistance (*hot*) when resistance (cold) is known;

---

[1] The *watt* is the unit of rate of expenditure of energy, and is equal to ten million ergs per second, or to $\frac{1}{746}$ of a horse-power. A current of one ampere, flowing through a resistance of one ohm, spends energy in heating at the rate of one watt. One watt is equivalent to 0·24 calories per second, of heat. That is to say, the heat developed in one second, by expenditure of energy at the rate of one watt, would suffice to warm one gramme of water through 0·24 (Centigrade) degrees. As 252 calories are equal to one British lb. (Fahrenheit) unit of heat, it follows that heat emitted at the rate of one watt would suffice to warm 3·4 pounds of water one degree Fahrenheit in one hour; or one British unit of heat equals 1,058 watt-seconds.

add to the known number of ohms 1 per cent. fo
Centigrade degrees, or for every $4\frac{1}{2}$ Fahrenheit deg

To find maximum permissible current, if th
temperature θ is prescribed as a limit.

$$\text{Max. permissible current} = \sqrt{\frac{\theta^\circ\,\text{C} \times \text{sq. cm.}}{355 \times \text{resistance}}}$$

or

$$\text{Max. permissible current} = \sqrt{\frac{\theta^\circ\,\text{F} \times \text{sq. inche}}{100 \times \text{resistanc}}}$$

EXAMPLE.—A coil has 450 sq. in. of surface, and a resis
of 15 ohms. It is required to know what is the largest
can carry continuously without heating more than 30° F.
surrounding air. Here the maximum current will be 3 a

If we assume that a safe limit of temperature
(or 50° C.) higher than the surrounding air, then t
current which may be used with a given electro
expressed by the formula :—

$$\text{Highest permissible amperes} = 0{\cdot}95\sqrt{\frac{s}{r}},$$

where s is the number of square inches of surface o
and r their resistance in ohms.

Similarly, for *shunt coils* we have :—

$$\text{Highest permissible volts} = 0{\cdot}95\sqrt{s\,r}.$$

The magnetizing power of a shunt coil, supplied
number of volts of pressure, is independent of its le
depends only on its gauge, but the longer the wi
will be the heat waste. On the contrary, when the
of supply is with a constant number of amperes o
the magnetizing power of a coil is independent of t
of the wire, and depends only on its length ; but
the gauge the less will be the heat waste.

Owing to the cooling effect of the air-curre
running, it is found that when a dynamo is stop
end of a long run, the surface temperature immedi

above what it was when running, as the heat which is being conducted outwards from the hotter interior is not now so rapidly got rid of. In the Admiralty specifications it is laid down that after the end of a long run of six hours, no part of the machine shall at the end of one minute after stopping show a greater rise than 11° C. (= 20° F.) above the surrounding air. This is absurdly low; and for ordinary engine-room work a rise three or four times as great is perfectly safe. Kapp allows 1·5 sq. in. (= 9·7 sq. cm.) for each watt lost in the armature; and 2·5 sq. in. (= 16·2 sq. cm.) per watt in the field-magnet. Esson finds that on armatures running at ordinary speeds, there will be a rise of 35° C. if for every watt wasted in heating 1·13 sq. in. (= 7·3 sq. cm.) be allowed. The formula given above for field-magnets would show for the same rise a minimum surface of 1·5 sq. in. (= 9·7 sq. cm.) per watt. Esson finds an approximate rule for different speeds to be:—

$$\theta^\circ (\text{C.}) = \frac{55\,w}{s\,(1 + 0{\cdot}00018\,v)};$$

where s is given in square inches, and v is the peripheral velocity in feet per second. If these are given in square centimetres, and metres per second, respectively, the rule becomes:—

$$\theta^\circ (\text{C.}) = \frac{354\,w}{s\,(1 + 0{\cdot}0006\,v)}.$$

Some calculations about the greater heating of interior layers have been given by Mr. Joyce.[1]

The following rules are useful for calculating the windings for machines of same type, but of varying size, or output.

To reach the same limiting temperature with equal-sized bobbins wound with different-sized wire, the cross-section of the wire must vary as the current it is to carry; or in other words, the current density (amperes per square centimetre) must remain constant.

To raise to the same temperature two similarly shaped coils, differing in size only, and having the gauge of in the same ratio (so that there are the same number on the large coil as on the small one), the currents such that the squares of the currents are proportion cubes of the linear dimensions.

---

[1] *Journ. Inst. Electr. Engineers*, xix. 248, 1890.

Similar iron cores, similarly wound with lengths proportional to the squares of their linear dimensi when excited with equal currents, produce equal forces at points similarly situated with respect to the W. Thomson, *Phil. Trans.*, 1856, p. 287.)

Similar machines must have ampere-turns propor the linear dimensions, if they are to be magnetize an equal degree of saturation. (J. & E. Hopkins *Trans.*, 1886, p. 338.)

If two machines are to give same electromotive- diameter of the wire of the coils must vary as t dimensions.

If, in altering the field-magnets of a machine of a capacity, the lengths of the several portions of the circuit remain the same, but the several areas ar then the wire for rewinding must have its cross- area altered in proportion to the periphery of the s the cores.

The resistance of a coil, the volume of which is kn which is wound with (round) copper wire of diamete metres, enlarged by insulation to a diameter of D mil can be calculated by the following rule, which is base assumption that the partial bedding of the convolutio of 10 per cent. more wires being got in than would be if they were exactly wound in square order. This fi only be approximate, as the amount of bedding vari what with the relative thickness and pliability of the of insulating materials, as well as with the gauge of If v be the volume in cubic centimetres, the resistanc coil in ohms (cold) will be

$$r = 0{\cdot}0244 \frac{v}{D^2 d^2}.$$

If v be expressed in cubic inches, and D and d in mils. (1 mil = ·001 inch), then the approximate formula becomes

$$r = 960{,}700 \frac{v}{D^2 d^2}.$$

LENGTH AND DIAMETER OF ARMATURES.

Various rules have been given for the ratio between the length of an armature and its diameter, embodying the results of practice.

In the case of two-pole dynamos the usual dimensions for ring armatures vary from $L = \frac{1}{2} d$ to $L = 1\frac{1}{2} d$; $L = d$ being frequent. The symbols here refer to measurements on the unwound core. For drums $L = 2 d$ is frequent, though the values $L = 1\frac{1}{2} d$ and $L = 3 d$ are also found.

SECTION OF FIELD-MAGNETS.

Comparison of the machines of various makers shows that for ring machines the usual practice is to allow for magnet-cores of ring machines a cross section 1·66 times that of the armature core, if of wrought iron; or 3 times, if the magnet core is of cast iron. For the magnet-cores of drum machines the usual figures are 1·25 and 2·3.

The question sometimes arises what is the best *shape* of section to give to magnet-cores. This point is readily answered by considering the geometrical fact that of all possible forms enclosing equal area the one with least periphery is the circle. For facilitating comparison, the following table exhibits the relative lengths of wire required to wind round various forms of section enclosing equal area; the area of the simple circular form being taken as unity, and allowance made for thickness of winding.

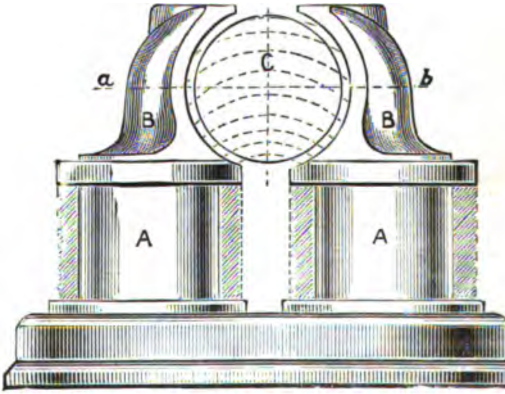
Circle	3·54
Square	4·00
Rectangle, 2 : 1	4·24
Rectangle, 3 : 1	4·62
Rectangle, 10 : 1	6·91
Oblong made of one square between two semicircles	3·76
Oblong made of two squares between two semicircles	4·28

Two circles side by side .. ..
Two circles, but wire wound round both together ..
Three circles „ „ „ „ each separately
Four circles „ „ „ „ „ „

SYMMETRY OF FIELD-MAGNETS.

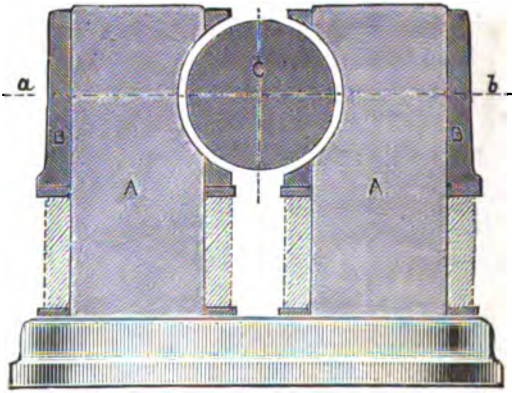
It was pointed out on p. 206, that in two-pole si
field-magnets the field is unsymmetrical, being muc

FIG. 284.



OLD FIELD-MAGNET OF THE ALSACIAN COMPANY

FIG. 285.



NEW FIELD-MAGNET OF THE ALSACIAN COMPANY

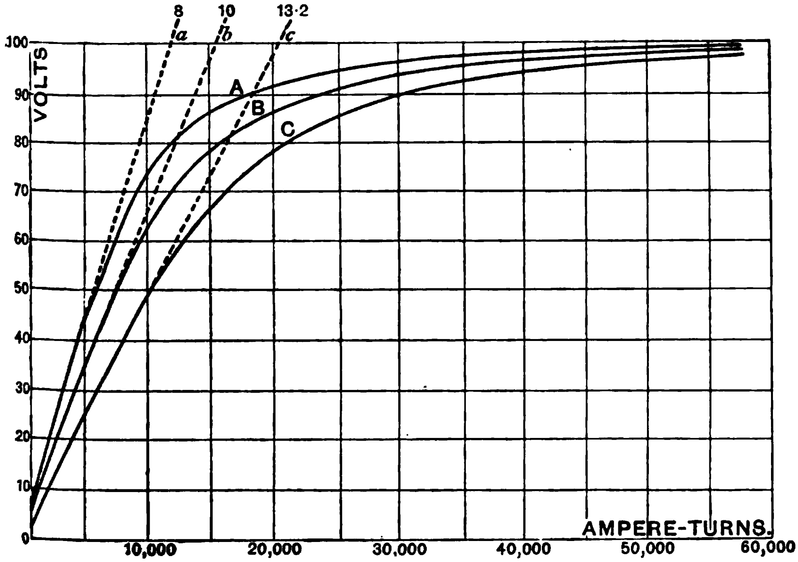
between the inner horns than between the outer ho
pole-pieces, if the poles are shaped away as in Fig. 1

This produces several evil results. First~~ly~~, the armature is attracted downwards as a whole (see p. 387); secondly, the armature, if ring-wound will be electrically out of balance, owing to the unequal magnetic fields at opposite ends of a diameter; thirdly, the neutral points for non-sparking will not be at opposite ends of a diameter. Fig. 284 depicts a 60-kilowatt dynamo of the Alsacian Company which had these defects, and was replaced by the more massive form shown in Fig 285, having cast-iron polar caps that slip on over wrought-iron cores.

EFFECT OF WIDENING THE GAP-SPACE.

The effect of widening the gap-space is in every case to cause a larger amount of energy to be spent in maintaining

FIG. 286.



CHARACTERISTICS WITH DIFFERENT GAP-SPACES.

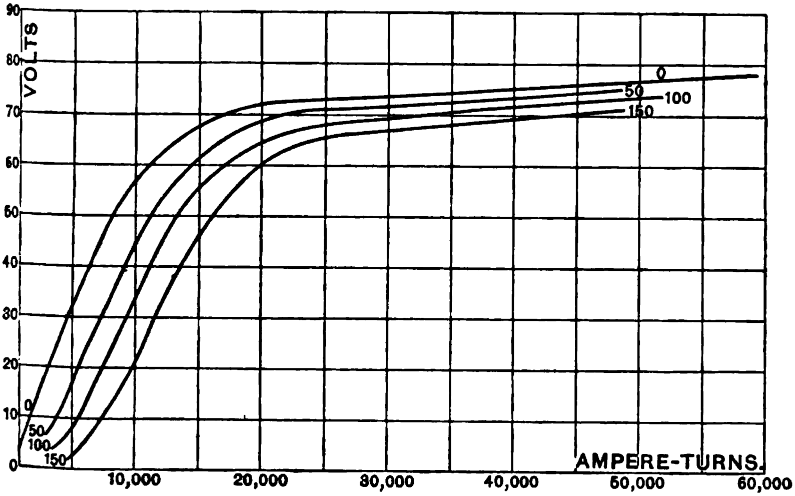
the magnetic field across the gap. Or, in other words, more ampere-turns are required on the field-magnet. It also has some other results. It slightly increases the leakage coefficient *v*. It enables more copper or thicker con be wound on the armature, diminishing its internal r and, if the armature has not been loaded beyon point of sparklessness, increases the output of the It has the further not unimportant result of incre reluctance in the path of the cross-magnetizing motive-forces, and diminishes their prejudicial actio ideas as to the first of these effects may be gath considering the characteristic curves given by A Fig. 286, showing the result of widening a gap-s 8 to 10, and then to 13·2 millimetres. Here we fin initial slopes of the characteristic right are given whose tangents are inversely proportional to the gap heights *c d*, *b d*, and *a d*, are inversely proportion numbers given as the widths of the gap-spaces. noted that for the upper part of the characteristics lines approach one another. Obviously the sugge the intensity of field of a dynamo is in inverse ra gap-space does not hold for dynamos at the worki of excitation.

INTERFERENCE OF ARMATURE FIELD.

As explained in Chapter IV., p. 76, the armatu tends to cross-magnetize, and, if the brushes have lead (or in a motor a backward lead) tends also t netize the field. We saw on p. 87 that the positi neutral point for non-sparking is affected by this int and on p. 285 we learned how to compensate the dem effect. We have now to consider the matter furthe point of view of dynamo design.

In the first place, let us examine the behaviou existing dynamo, by observing the relation be voltage and the amount of excitation, at some speed, under varying conditions of load. Let the to the brushes be varied as required to fulfil the co sparklessness. First let a curve be found with zero current; then with a 50 ampere load, then with 10 and so forth. The experiments should be made in each case by beginning with the highest excitation (and smallest angle of lead) and gradually diminishing the excitation (and increasing the lead) until a sparkless position can no longer be found for the brushes. This dynamo[1] was intended for a normal output of 150 amperes at 70 volts. It will be found that in each case, the smaller the load the more may the excitation of the field be diminished before the state of things is reached that no neutral point can be found. In other words, there will always be some definite relation between the ampere-turns on the armature, and those on the field-magnet which fixes the working limit of sparklessness. We shall presently enquire into this relation. For the present it may be remarked that these load-curves[2] give us much information as to the necessary windings of the field-magnet, how

FIG. 287.



LOAD-CURVES OF A DYNAMO.

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[1] See Arnoux in *Bull. de la Soc. Int. des Électriciens*, vi. 61, 1889.

[2] For other examples of load-curves see Esson in *Journal Instit. Electrical Engineers*, xix. 152, 1890; and Kapp in *Proc. Instit. Civil Engineers*, Feb. 1889.

many ampere-turns must be contributed on open
the shunt coil, and how many compensating am
must be added by the series coil in order to ke
voltage.

LIMITS OF LOAD AND NON-SPARKING PO

Two things limit the output of a dynamo: the
its armature conductors, and sparking at the brush
a dynamo, if by widening the gap a little and rev
armature with copper wire of double cross-section,
its resistance to one half, we may then take from
current with no more heating than before, provi
does not spark. Such a reconstituted machine
output would clearly cost less than two of th
pattern. But the limit of such an augmentation of
by increasing the ampere-turns on the armature
very soon; for the cross-magnetizing tendency
and the lead increased, and the demagnetizing tend
than doubled by doubling the ampere-turns of the
These perturbing effects may be all included under
name of *interference* used in the previous parag
have been investigated more or less fully by Hopk
more completely by Swinburne[2] and by Esson,[3] wh
mainly occupy the remainder of this chapter.

It has been pointed out, on p. 84, that b
individual sections of the armature winding po
induction, the reversal of the current in them in
commutation as they pass the brush requires th
of an impressed electromotive-force; and th
accomplished by giving the brush a lead (for
dynamo, backward in a motor) so that that sectio
the current is to be reversed is at that time passing t

---

[1] *Philosophical Transactions*, 1886, pt. i., p. 331; and *Ele*
Dec. 1886.

[2] *Journal Instit. Electrical Engineers*, xv., 540, 1886; and
265, 1890.

[3] *Ibid.*, xix. 118, 1890; and xx. 265, 1891; also *Electric*
213, 1890. See also *Electrical Review*, series of articles on Synt
Dynamos, 1890.

fringe of the magnetic field. The stronger the current to be reversed, the stronger is the field necessary for sparkless reversal. But the field under the "trailing" horn of the pole-piece (or in a motor, the "leading" horn), near which commutation must take place is, as we have seen (Figs. 63 and 67), weakened by the interference of the armature. Now the cross-magnetizing action of the armature tends to send magnetic lines up (see usual diagram Fig. 62, p. 78) both sides of the ring core, which tend to cross the gaps and return through the masses of the pole-pieces; the strongest cross-magnetizing force in the gaps being under the tips of the polar horns. This cross action opposes the normal flux of magnetic at the top right and bottom left corners (of Fig. 63), and helps it at the other two. The cross-magnetizing magnetomotive-force under the pole-tips (assuming the gaps alone to offer any appreciable reluctance) is equal to $\frac{4}{10}\pi$ times the ampere-turns of all the conductors that lie in the gaps, or within the angle of polar span ψ. Using the usual symbols—C for the number of conductors around the armature, and i_a for total armature current—we have for the total ampere-turns on the armature $\frac{1}{2}\,C \times \frac{1}{2}\,i_a$, of which $\psi \div 180^\circ$ are effective, and of which the half may be taken as the part operative in either place where the cross-circuit crosses a gap. If ψ is taken at 120°, the cross-force under the tip will be

$$\tfrac{1}{2}\,C \times \tfrac{1}{2}\,i_a \times \tfrac{1}{2} \times \tfrac{4}{10}\pi \times \tfrac{120}{180} = C\,i_a \times 0{\cdot}104;$$

or equals the ampere-turns[1] on the armature multiplied by 0·416. Now let us see what number of ampere-turns on the armature would produce a cross-force in th exactly balancing the normal magnetizing force the neutralize the field under the pole-tip. In that cas reversal would be impossible, and so we should h tained the limit of load. Now the difference of potential in the gap (or that part of the magnetom that is spent therein) is equal to the product of th reluctance of the gap into the flux across it. If l_2 be across the gap and A_2 the polar area, the relucta gap is $l_2 \div A_2$, and the magnetic potential differe $= N\, l_2 \div A_2$. Now call the length of the armatur the pole-face, parallel to the axis, L; the brea pole-face measured along the curve from tip to radial depth of the core r; and its sectional are may assume that in the core the magnetization is $B = 17{,}000$. Then we have the following relations

---

[1] This term is here used precisely as for any electromagnet. In two-pole drum-armatures it is half the armature current multiplied by half the number of external conductors. In multipolar machines (wound with parallel grouping) it is equal to total current multiplied by total number of conductors and divided by the square of the number of poles. In Esson's paper of 1890 (*Journal I. E. E.*, xix. 143), the term ampere-turns was used in a different sense, namely, as the product of the total number of conductors into the current carried by each. This is the same thing to which in his paper of 1891 (*Journal I. E. E.*, xx. 266) he gave the not very apposite name of 'volume,' but which would have been better described as the total circulation of armature current. The name used here for this quantity is the *circumflux*. For two-pole machines the circumflux is twice the ampere-turns; for four-pole machines, four times, &c..

$$N = 17000\, A_1\,;\; A_1 = r\,L\,;\; A_2 = b\,L.$$

Substituting these in the preceding expression, and out L, we get—

Magnetic potential in gap $= 17000 \times r \times l_2$

Equating this to the cross-force we get—

$$\frac{Ci}{4} = \frac{40900\, rl_2}{b}.$$

For some purposes it is more convenient—part relation to multipolar machines—to consider not t turns of the armature, but the effective circulation o reckoned by multiplying together the number o conductors and the current carried by each indep its direction. This quantity, here denoted by the we shall call the *circumflux*.[1] It is equal to the the whole armature current, into the whole armature conductors, divided by the number of po two-pole dynamo we then have as the limiting l armature:—

$$Q = \frac{C\, i_a}{2} = \frac{81800\, r\, l_2}{b}.$$

---

[1] Called by Esson at one time the "ampere-turns," and later of the armature current. See preceding foot-note.

Esson,[1] gives the result of observation of a number of modern dynamos by different makers, and found the actual numerical coefficient to vary from 61265 to 95905 for ring machines, with a mean of 85000, differing little from the theoretical 81800 given above.

From the foregoing it appears that the maximum load which an armature can carry, within the limit of sparklessness, is directly proportional to the radial depth of core, and to the length of the gap, but inversely proportional to the breadth of the polar span. If, therefore, taking an existing machine whose load is just within the spark limit, we wish to make it carry a heavier load (or more copper on the armature) we may do so either by increasing the radial depth of the core-disks, or by increasing the gap-space (whether wanted for copper and clearance or not), or lastly, by diminishing the breadth of span of the polar faces. The first of these causes means a new armature; the second requires the pole-faces to be bored out afresh, and also means some (not large) addition to the magnetizing power of the field-magnet; the third has the effect of concentrating the magnetic flux, therefore, lowering slightly the permeability, and necessitating either a slightly higher speed or a slight increase in the magnetizing power.

The circumflux or polar circulation of armature current permissible for an armature of given diameter may be given in terms of the diameter by assuming (for ring two-pole armatures) that $b = 1{\cdot}05\,d$; $r = 0{\cdot}1d$; and $l_1 = 0{\cdot}05\,d$.

Substituting these values, we get

$$Q = 390\,d.$$

Esson takes 400 d (centimetres) as the limiting value of Q, for rings, and 600 d as the value for drums. Kapp allows 1000 ampere-turns (or 2000 circumflux in case of two-pole machine) for each inch of diameter above 12 inches, as a safe load.

We are now ready to consider the safe output (watts) of a dynamo in terms of its dimensions.

---

[1] *Journal I.E.E.*, xx. 142, 1890.

The gross output of a bipolar dynamo is—

$$W = E\,i_a = n\,N\,C\,i_a \div 10^8, \qquad \text{(see}$$

or for a multipolar dynamo

$$W = n\,N\,\frac{C\,i_a}{p} \div 10^{\circ}\,;$$

where p stands for the number of *pairs* of poles
the value of Q, the circumflux of armature curre
$C\,i_a \div 2\,p$; whence

$$W = 2n\,N \times Q \div 10^8.$$

Now assume (as fair average of actual cases)
pieces together cover $\frac{7}{10}$ of circumference (or 2·2
that the value of B in the gap is 5000. Then, if I
of armature core (cms.), the working area of the
through which magnetic lines go in or out = 2·2
whence area of any one polar part is $2{\cdot}2\,d \times$ L
the flux of magnetic lines through any one pole w
times this ; or for the total flux through the $2\,p$ pol

$$N = p \times 5000 \times 2{\cdot}2\,d \times L \div 2p = 5500\,d \times$$

Inserting this value we have—

$$W = 11000 \times d \times L \times n \times Q \div 10^8$$

But, according to Esson, as above, Q = 400 d fo
600 d for drums, as the safe loads. Inserting these
get—[1]

$$\left\{\begin{array}{ll} \text{for rings} & W = d^2\,L\,n \times 0{\cdot}044 \\ \text{for drums} & W = d^2\,L\,n \times 0{\cdot}066 \end{array}\right\}$$

Now d^2 L is proportional to the volume of the
core. Hence we conclude that the output is prop
volume and to speed, and is independent of the
poles and of the grouping of the armature conducto

---

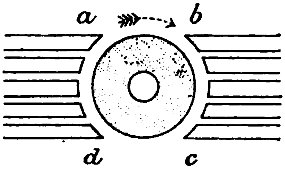
[1] Esson, taking slightly greater width of pole-pieces, gets 0·048
the respective co-efficients. Snell (*Journal I.E.E.*, xx. 197) finds
give as their co-efficients, when translated into centimetres and sec
spond, 0·0375 and 0·056 respectively.

finds it (for equal surface temperature) to increase as the 3½ power of the diameter, which is slightly higher than the volume, probably because of the somewhat higher peripheral speeds attained by large armatures.

DEVICES FOR CHECKING SPARKING.

Seeing that the cross induction is responsible for the weakening of the field needed for reversing the current at commutation, various devices have been suggested for checking the evil. One is to apply an auxiliary reversing pole.[1] Another, applicable to field-magnets with double circuit (such as Nos. 8 and 24 of Fig. 119), is to make a deep nick between the right and left-hand halves, and so throttle the cross-flow of magnetic lines. Another suggestion, made by the author of this work some years ago, was to construct the field-magnets of pieces of iron, with longitudinal gaps, as in Fig. 288. Another suggestion, by Mr. Sayers, is to notch the pole surface, near the pole-tip, with a deep notch, so as to concentrate the field, and supply a "fringe" suitable for reversing.

FIG. 288.



DESIGN OF MULTIPOLAR DYNAMOS.

The advantage of using Q (the circumflux) rather than the ampere-turns, in the foregoing investigation, is that the spark limit of load depends not on the total ampere-turns or action of the whole armature as an electromagnet, but on the circulation of current per pole. Hence the results obtained

---

[1] See Swinburne (*Journal I.E.E.*, xxx. 105, 1890); and Housman (*ib.*, xx. 299, 1891), who maintains that if B = 7000 under the pole-piece, the auxiliary field for reversing must be at least = 3000.

are available immediately for multipolar as well
machines, as was pointed out by Esson, to whom
credit of this conception.

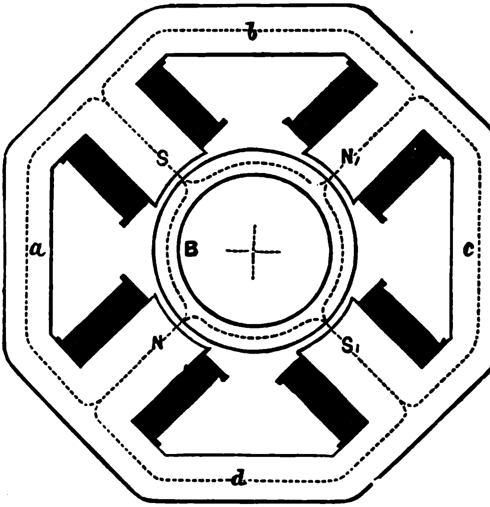
The formula at foot of p. 438 may now be re-w

$$Q = \frac{277\ B\ l_2}{\psi};$$

where B is the strength of field in the gap-space.

If we assume the limiting values of Q, and the
of B, as already determined, then if ψ, the angle of
be taken at 130° it follows that the radial depth l_2
space must not be less than $\frac{1}{28}d$ for rings, nor les
for drums. Then, if in order to make a la
machine, whilst keeping to two poles, we increase
either increase l_2 or B, or else diminish ψ, or pe

FIG. 289.



FOUR-POLE RING DYNAMO (BROWN).

combination of these processes, which in any case
greater expenditure of power in maintaining the
gap-space. Herein lies the advantage of multi

struction for large outputs. Consider such a form as Fig. 289 with four poles. To prevent undue leakage from pole to pole the distance between pole horns is wider relatively to the polar span than in a two-pole machine; and, for an equally high value of B in the gap-spaces, the section of the ring is reduced, its diameter enlarged, and with its diameter its cooling surface. For drum-wound machines there is, in addition to such gains, the additional advantages that end-connexions are much simpler, and ventilation easier, than for two-pole machines. But does it pay the constructor to make the change? There is a little more labour in tooling castings; but will he save copper? A case will show that, beyond a certain limit of size, there is a saving. Consider a two-pole drum; $d = 50$; $L = 90$; $B = 5000$ in the gap; $\psi = 130°$. Then it will not be sparkless unless the gap-space l_2 is at least 3·2 cm., or about 0·9 cm. more than is needed for windings and clearance. If, to make this work sparklessly, we diminish the gap and increase B to 7,000, or diminish ψ to 100°, we still gain nothing in magnetizing power. Now substitute a four-pole drum: $d = 84$; $L = 45$; $B = 5000$. With this increased diameter, the gap-space may be reduced to a minimum, and the magnetizing power may be reduced by at least 30 per cent., and the total weight of iron by nearly 40 per cent., which will more than pay for the extra labour of tooling. Esson states that the cost of a four-pole dynamo, of output W at speed n, may be put as being equal to that of two dynamos, each of output $\frac{1}{2}$ W at speed $2n$, and so forth. The cost of field-magnet castings is reduced, and their weight lessened, when, as in the large machines of Siemens and Halske (Plate XI.) the ring is of such large dimensions that the field-magnet can be placed internally.

For large output machines, multipolar forms are, then, preferable to bipolar; firstly, because they give their maximum sparkless output with minimum clearance, and therefore with minimum weight of copper on magnet; secondly, because they keep cooler, so that for a given volume of core and winding there is actually a greater output. Snell compared a four-pole drum machine of 60 cm. diameter

with a two-pole drum of same diameter—the
300 amperes at 250 volts, the other 70 amp
volts, or only about ⅔ the output. Multipolar ma
one further advantage over two-pole machines, in
length may be varied relatively to the diamet
much loss in economy. In the case of drum wi
is very marked. For two-pole drums the best p
L = 3·3 *d*, and if L = 2 *d* there is an increase of 5
the copper used, or if L = 1½ *d* the increase is c
cent., whereas for four-pole drums L = ½ *d*, uses s
as L = 2 *d*; and for a six-pole drum L = ¼ *d* is ju

BEST THICKNESS OF GAP-SPACE.

Professors Ayrton and Perry have investigated[1] the
best thickness of the conductors on armatures. Usi
notation as in the rest of this book, their argument is a
The power developed by the armature may be written

$$w = E\, i_a = \frac{n\, C\, N}{10^8}\, i_a;$$

or writing a for the number of amperes per square cent
cross-section of the armature, r for the external radius
core, and t for thickness of external winding on armatur

$$C\, i_a = 2\, a \times 2\, \pi\, r\, t;$$

whence

$$w = \frac{4\, \pi\, r\, n\ N . t\, a}{10^8}.$$

Now, writing ρ as the resistance of the armature
centimetre cube (including copper and insulation), the
per cubic centimetre in heating will be = ρ ; a
wasted in heating the external conductors on the arm
$= 2\, \pi\, r\, t\, l\, \rho\, a^2$; where l is the length of the external c
the armature. Now let the rise of temperature above
surrounding air be called θ (degrees C.), and let z s
amount of heat (expressed in watts) emitted per squa
of surface, for an excess of temperature of 1° C. above t
ing air. Then the watts emitted as heat from the w

---

[1] See their paper, *Phil. Mag.* for June, 1888.

surface of the armature will be $= z\,\theta\,2\,\pi\,r\,l$. Equating the watts generated and the watts emitted at the surface, we have

$$2\,\pi\,r\,t\,l\,\rho\,a^2 = z\,\theta\,2\,\pi\,r\,l,$$

$$t\,\rho\,a^2 = z\,\theta,.$$

$$t\,a^2 = \frac{r\theta}{\rho}.$$

Now write a_1, θ_1, w_1, and N_1 as the highest permissible values of a, θ, w, and N respectively. And write q for $\sqrt{z\,\theta_1/\rho}$. It appears that the value of q in the best modern machines is about 288. Now $ta = q\sqrt{t}$. Inserting this value, we get

$$w_1 = \frac{4\,\pi\,r\,n}{10^8}\,N_1\,q\,\sqrt{t}.$$

Now by the principle of the magnetic circuit, p. 177 we have

$$N = \frac{4\,\pi\,S\,i/10}{\dfrac{2\,(d+t)}{A_2} + \Sigma\,\dfrac{l\,v}{A\,\mu}};$$

where d is the clearance between the surface of the armature windings and the curved face of the polar surface of the magnet, A_2 the effective area of the polar surface, and $\Sigma\dfrac{l\,v}{A\,\mu}$ the magnetic reluctance of the iron parts of the magnetic circuit. Assume that N is worked up to its highest permissible value N_1, then we may write

$$w_1 = \frac{4\,\pi\,r\,n\,q}{10^8}\,\sqrt{t}\,\frac{4\,\pi\,S\,i/10}{\dfrac{2\,(d+t)}{A} + \Sigma\,\dfrac{l\,v}{A\,\mu}}.$$

This expression varies in value when the value given to t is varied, and it can be shown to have a maximum when the value of t is such that

$$\frac{2\,t}{A_2} = \frac{2\,d}{A_2} + \Sigma\,\frac{l\,v}{A\,\mu}.$$

That is to say, the permissible continuous output of the machine is a maximum when the thickness of the winding on the armature is such that *the magnetic reluctance of the space occupied by the winding on the armature is equal to the reluctance of the rest of the magnetic circuit.*

Assuming that practically the whole of the gap-s armature core and pole-piece is filled with armature above rule amounts to saying that, given the co armature, the dynamo ought to be worked at such excitation that its total magnetic reluctance is run up t great as that of the gap-space alone. This is indeed the diacritical stage of magnetization, the permeability i magnetic circuit—iron and air together—being at this to half its initial value. But we see from the researches and Esson that to prevent sparking a wider gap-space than that occupied by copper and clearance.

CHAPTER XVII.

ARC-LIGHTING DYNAMOS.

FOR supplying arc lights, it is usual to arrange the lamps all in series, even to as many as 60 or 80 lights, and to provide a dynamo-machine which will give a constant, or nearly constant, current at a sufficiently high voltage. The usual current for which arc lamps are designed is 10 amperes. Some of the Thomson-Houston lamps are designed, however, for 6·8 amperes, and Ball arc-lamps for 4 amperes. These are therefore exceptions. On the other hand, the arc lamps used for search-lights and lighthouse work are designed to take larger currents, up to 200 amperes or more. Continuous-current voltaic arcs cannot be maintained burning steadily unless they are fed at a pressure of about 40 to 45 volts for each lamp. If the pressure is insufficient, the arcs will give out a hissing sound. The steady arc behaves as though it exercised a counter electromotive-force of about 39 volts. When arc lamps are to be used in parallel with one another, the mains must have a greater difference of potential than 45 volts—55 or 60 volts is preferable—in order that additional resistances may be introduced to steady the current through each lamp. Such additional resistances are not necessary when a number of arc lamps are used in series, as they help to steady one another. The dynamo ought, however, to be so governed as to keep the current constant, at the same strength, no matter how many or few lamps are intercalated in the circuit.

In arc-lighting in series, the function of the dynamo is to keep the amperes constant; whilst each lamp is provided with a shunt device which governs the movement of the carbons, so that the feeding of them shall keep the length of

the arc, and the volts at the terminals of the lam
mately constant.

We may take it, therefore, that a system of
series will require a dynamo giving a current
amperes, and a pressure, when all the lamps ar
nearly 1000 volts. This allows 45 volts per lamp,
more for the resistance of the wires between eac
the next.

Constant current dynamos are also need
purposes of municipal lighting by means of sp
lamps, with thick carbon wires instead of thi
connected in series, so that the same current fl
sively through a large number of them.

It was suggested by Deprez in 1881, that by
compound winding, consisting of an initial excit
shunt excitation combined, a dynamo might be
to give a constant current at constant speed. T
tion which underlay his reasoning, that the m
proportional to the exciting power, is, we know, n
except for the early and unstable stage of ma
and all attempts to produce a practical compound
this purpose have failed.

Owing to the circumstance (p. 110) that the
dynamo is proportional to the current, it is found
a dynamo with well-excited field-magnets is driv
own engine, with constant steam-pressure, but not
run at a fixed speed, it will of itself run very nea
speeds as shall keep the current constant. But a
of governing is inadmissible in those cases where
has to drive at a constant speed, other modes of
current constant are resorted to, which are d
Chapter XXVII. on Regulators.

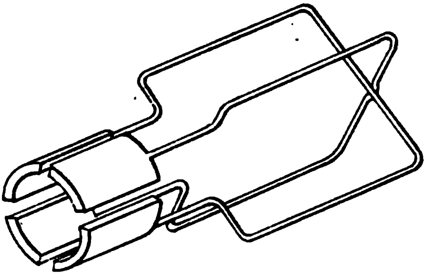
For the production of constant currents at
voltages as 2000 to 3000 volts the ordinary ring
armatures, wound in a closed coil, in numerous s
provided with a commutator consisting of numer
packed parallel bars, have not been found entirely
for the commutator of this type is liable to give

the high pressure, and to deteriorate under the action of long sparks flashing over its surface from brush to brush under the wide alterations of lead that are inseparable with this mode of working. In Deprez's experiments on transmission of power to a distance by currents at very high pressure, machines with Gramme armatures wound with very fine wire were used, giving from 4000 to 6000 volts. They gave incessant trouble from the breaking down of the resistance. Nevertheless, good results have been obtained more recently by Messrs. Paterson and Cooper, and also by Lahmeyer of Frankfort, in the use of high voltages in machines having ordinary commutators with many segments. Experience, however, is in the main against the use of armatures of this type. More simple forms are needed that will not break down under the conditions of work. These forms are usually associated with other modes of construction in which the armature winding does not constitute a closed coil.

OPEN-COIL DYNAMOS.

As explained on p. 40, it is possible to construct armatures in which the separate coils or sections of the windings are

FIG. 290.

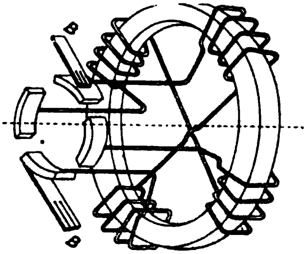


SIMPLE OPEN-COIL ARMATURE.

not united together into one closed circuit. An example is given in Fig. 290. This diagram (which should be compared with Fig. 24, p. 37) shows an armature consisting of two

separate loops, set in planes at right angles to o
so that when one is passing through the inactive
other is in the position of maximum action.
reason why these two loops should not have eacl
2-part commutator like that of Fig. 24; and
brushes might press on both commutators. It
obviously more convenient to unite these two c
into a single one of four parts, as in Fig. 290;
will at once be seen that as this rotates betwe
of brushes one loop only will be in action at onc
loop being cut out of circuit for the time being.
clearly be possible to arrange any number of lo
in this way so that only that loop or coil which
through the position of maximum action should
the brushes, all the rest being meantime open-ci
ring armature wound in sections might of course
arranged, so that the pairs of sections had each
commutator; and Fig. 291 (which should be com
Fig. 31, p. 39) shows such a ring, but with the two
tors cut down and formed into a 4-part collector.

FIG. 291.

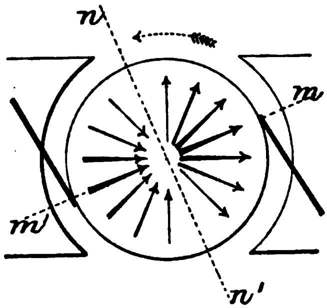


FOUR-PART OPEN-COIL RING ARMATURE.

It will be noticed that each coil is joined at t
the one diametrically opposite to it, and that the
of the coils pass to the commutator. As a matte
would make no difference in either of these arm
the wires which cross at the back all united where
In order further to follow the action we will refer t

This diagram represents by means of radial arrows the electromotive-forces induced in a loop or loops rotating (*left-handedly*, as it happens, in this figure) in a magnetic field (with N-pole on the left in this case). The action is a maximum along the line of the resultant magnetic field *m m'* (which would be horizontal were it not for the reactions explained in Chapter IV.), and is a minimum along the line *n n'*. The reader will remember that line *n n'* is the neutral line which lies nearly at right angles to the line of maximum magnetization; and that, for those armatures in which all the coils are joined together in a closed circuit, it is at *n n'* that the brushes have to be placed. But when each coil is independent of the others it is no use putting the brushes at *n n'*; they must be put at *m m'*; the line of maximum action coinciding in this case with the diameter of commutation. But those coils which lie very near the line *m m'* are undergoing induction very nearly as strongly as the actual pair that lie in that line: it would therefore naturally occur that the current might be simultaneously collected from more than one coil at once, either (1) by making the pieces of the commutators overlap, or (2) by connecting to the brushes that touch on the line *m m'* another pair having either a forward or a backward lead. If we now consider Fig. 293 we shall see this a little more clearly. This figure is a diagram of such an armature, the coils or loops being here represented merely by wavy lines.

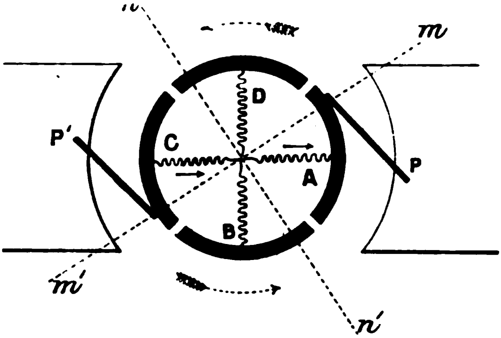
FIG. 292.



INDUCTION OF CURRENTS IN ARMATURE.

The wavy line A C may represent either a pair of coils such as there are in Fig. 293 on the ring, or may represent a single loop or group of windings round a drum. There is a pair of commutator-plates for A C, and another at right angles for B D. Coils A and C are just coming into the position of best action; they are delivering a curre brushes P P, and this current will accordingly increa and then decrease again. Meantime coils B and If the four parts of the compound commutator ea

FIG. 293.

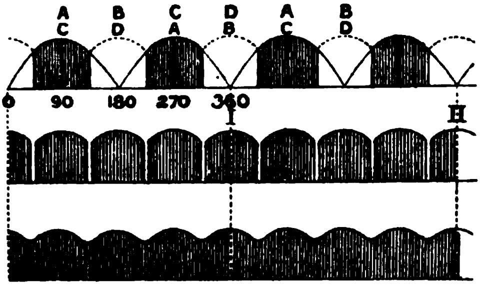


just a quarter of the circumference, it is clear tha comes into action its plane makes an angle of 45° and that just as it leaves contact with the brush m an angle of 45° on the other side, being in con intermediate positions; and so with each coil a the brushes. There will be a momentary break and a spark as the two successive segments pass brush, unless the brush touches both at once. bering that Fig. 29, p. 38, represents the alternati from a single loop or pair of coils, and that Fig represents the same currents rectified by the use two-part commutator, we shall be able to represen of our new arrangement by some such diagram a The angles marked below are reckoned from t line *n n'*. When coil A has gone round 90° position, it is in the position of maximum indu because the segment A of the commutator is its breadth, the current will be collected from 45 The shaded portions of the curve show the dis effect due to the coils A and C coming into circ two quarters of the rotation. The coils B and in the intervals, as indicated by the dotted lines. The induced currents will therefore present an approximate continuity depending on the arrangements of the commutator and the brushes. Fig. 295 represents the effect when there are gaps between the segments of the commutator; and it will be noticed that the currents, though all of the same sign, are discontinuous. If the brushes thus left contact with one segment of the commutator before the next come into contact there would inevitably be a considerable amount of sparking. Fig. 296 shows the result of making contact with one set before the other set is cut out; the induced current being now continuous, but with undulating fluctuations of strength. During the time when both sets of coils are in contact with the brushes, they are, of course, in parallel with one another. During this stage of the action the resistance of the armature is half as great as when one of the coils is cut out; but it is necessary to cut out the idle coil, otherwise some of the current from the active coil would flow back uselessly through the idle coil that was in parallel with it. During the time when the two sets of coils are in parallel they are not equally active. The induced electromotive-force is increasing in one and diminishing in the other; there is but a moment when they are equally active—when they make equal angles with *m m'*. At all other moments the higher electromotive-force of the more active

FIG. 294.

FIG. 295.

FIG. 296.



CURVES ILLUSTRATING THE PRODUCTION OF CURRENTS BY USING AN OPEN-COIL FOUR-PART ARMATURE.

coil tends to send a back-current through the less a
and the net electromotive-force with which they a
brushes will be the mean of their two separate elec
forces.

From what has now been said, it will be clear
coil armatures may be constructed either as rings,
disks. They may be arranged to run either in a
in a multiple magnetic field. The principal dyn
structed upon this plan are the Brush machine
Thomson-Houston machine : but there are a few ot
also come within the category of open-coil dynam

Brush's Dynamo.—One of the best known and le
stood of these machines is the Brush dynamo. I
form, and the disposition of the field-magnets
gathered from Fig. 297. The field-magnets are ver
tially built. The magnet heads are insulated with
the so-called vulcanised fibre, thoroughly varnish
field-magnet cores are, however, first surrounded w
sheet of copper, soldered together at the edges so
a continuous tube or envelope. The object of t
coating is to absorb the induced extra currents which
would be set circulating in the core whenever a v
the magnetism occurred. Over the copper envelope
four or five thicknesses of very heavy paper satu
shellac varnish to insulate the wire from the iron.
of the Brush dynamos there is a double winding,
"teazer" circuit being added to maintain the ma
the field-magnets when the main circuit is open
automatic regulator, described briefly in Chapter
used with arc-lighting Brush machines.

The armature—a ring in form, not entirely over-w
coils, but having projecting teeth between the coi
Pacinotti ring—is a unique feature. Though it so far
Pacinotti's ring, it differs more from the Pacinotti
than that armature differs from those of Siemens,
Edison, Bürgin, &c. ; for in all those the successiv
are united in series all the way round, and constitu
sense, one continuous bobbin. But in the Brush arma

is no such continuity. The ring itself was formerly made of malleable cast iron. The wire spaces were planed or milled out, and all angles and corners were carefully rounded. All iron parts which are to adjoin the wire of the "bobbins" are covered first with a layer of strong heavy canvas saturated with shellac varnish, and in the case of the armatures of the larger machines there are additional layers of tough paper saturated with shellac varnish. A sheet of strong cotton cloth inserted occasionally separates contiguous layers of wire from each other both in the armature bobbins and in the coils of the field-magnets. All the bobbins are wound by hand, in the same direction, and the inner ends of diametrically opposite bobbins are soldered together, and carefully insulated from all other wires and adjacent metal. The free outer ends of each pair of bobbins are separately carried along the shaft, through the journal, and connected to diametrically opposite segments of the commutator. In the "sixteen-light" machine the ring is 20 inches in diameter. In each of the eight coils there are about 900 feet of wire of ·083 inch gauge. Thus connected, the machine is adapted to deliver a current of ten amperes. By connecting the two bobbins of each pair in parallel, instead of in series with one another, the machine may be used to deliver a 20-ampere current. For electroplating, much stouter wires are used.

For each pair of coils there is a separate commutator. In the No. 7 size of machine, which is depicted in Fig. 297, there are eight coils on the armature, four commutators grouped in two pairs, and two sets of brushes. This size is commonly known as a "sixteen-light" machine, though it will, as now improved, supply from 24 to 25 arc lights.

The larger Brush dynamos ("sixty-light" machines) have twelve coils upon the ring, connected as six pairs. There are three pairs of brushes, and three pairs of commutators, each pair being set one-twelfth of a rotation (30°) in advance of the next pair. These machines have the enormous electromotive-force of nearly 3000 volts; and, with the recent improvements, will supply 60 or more arc lights in a single circuit. They formerly supplied 40 lights only.

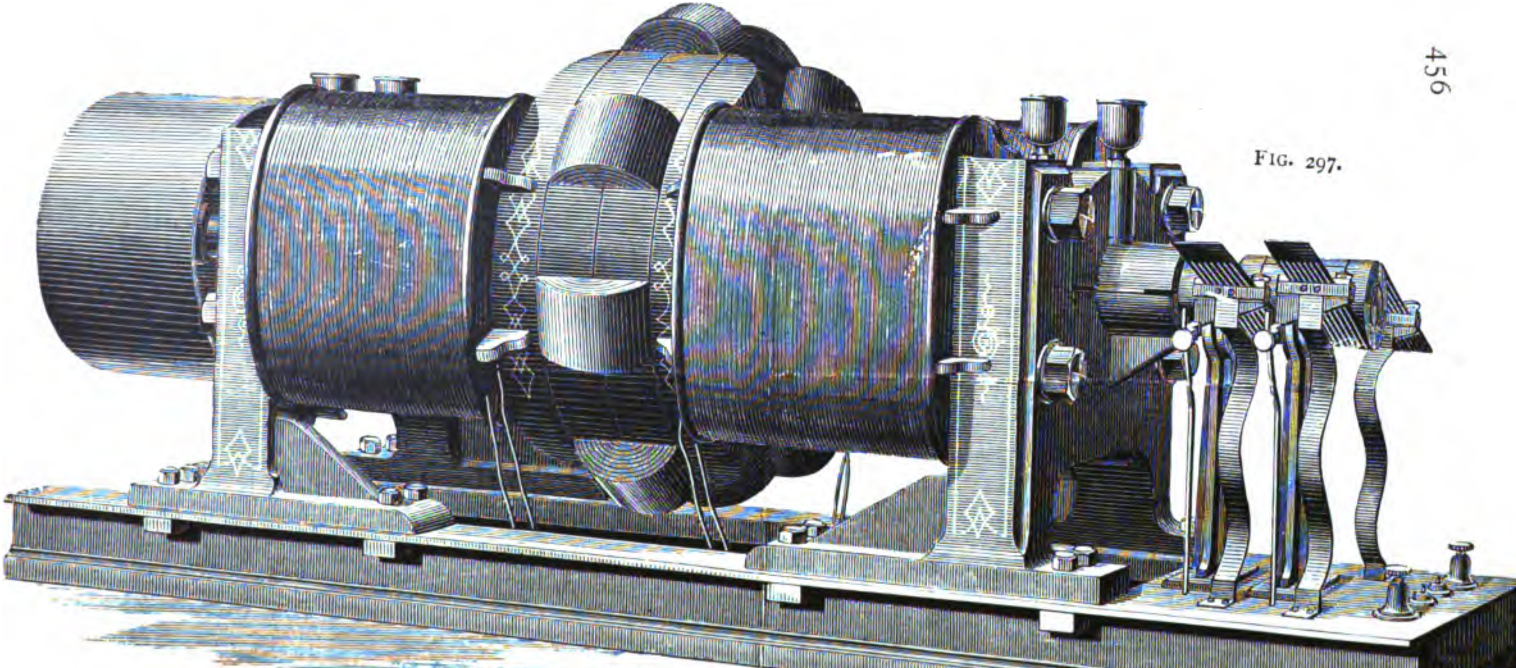
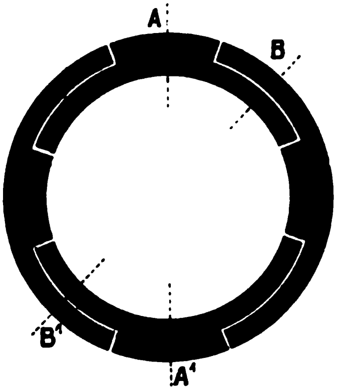


FIG. 297.

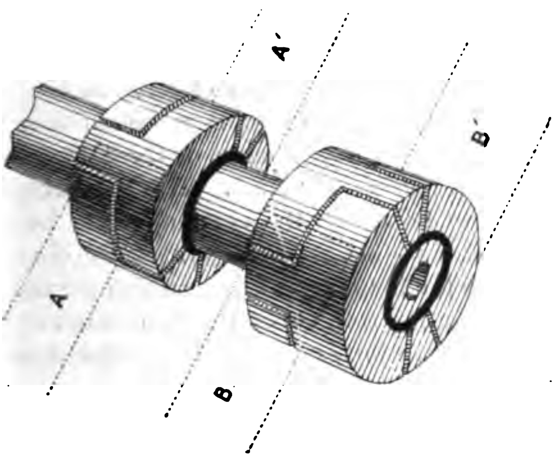
The brushes are arranged so as to touch at the same time the commutators of two pairs of coils, but never of two adjacent pairs; the adjacent commutators being always connected to two pairs of coils that lie at right angles to one another in the ring. Continuity is obtained in the currents by making the two parts of the commutator of each pair of coils overlap those of the commutator belonging to the pair of coils that is at right angles, one pair of brushes resting on both commutators. Fig. 298 is a diagram illustrating this device. Each pair of segments overlaps the other to the extent of 45°. Each of the two pairs of coils is thus cut out twice during a revolution; it is twice in circuit alone, as when the brushes are at A A′, and four times in circuit along with

FIG. 298.



PAIR OF OVERLAPPING COMMUTATORS.

FIG. 299.

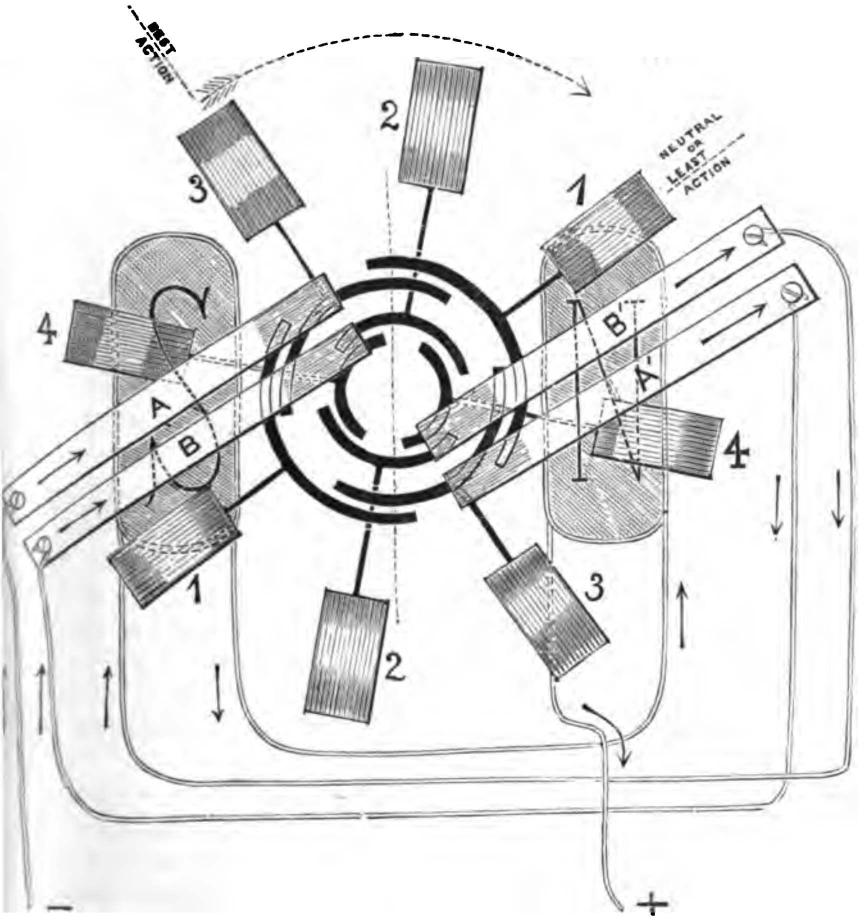


BRUSH COMMUTATOR FOR ARMATURE WOUND WITH FOUR PAIRS OF COILS.

the pair that are at right angles, when the brushe
B B′. Fig. 299 shows the way in which the comm
arranged in all eight-coil Brush armatures—that is, in
for supplying from one to twenty-five arc lights.
really four commutators here, corresponding to the
of coils, grouped in pairs ; one pair of commutators
one-eighth of a rotation (45°) in advance of the othe
be seen from this figure that while the brushes A
in dotted lines) are receiving current from *one pa*
only, the brushes B B′ are at the same instant rec
current from *two pairs* of coils which are joined i
with one another in consequence of both of their com
touching the same pair of brushes. The arrange
be still further studied by the aid of Fig. 300, which
trates the way of connecting the brushes with the ci
this figure the eight coils are numbered as four pairs,
pair has its own commutator, to which pass the out
the wire of each coil, the inner ends of the two c
united across to each other (not shown in the diag
the actual machine, each pair of coils, as it passe
the position of least action (*i.e.* when its plane is
angles to the direction of the lines of force in the
when the number of lines of force passing throug
maximum, and the rate of change of these lines
minimum) is cut out of connection. This is accomp
causing the two halves of the commutator to be
from one another by about one-eighth of the circ
at each side. In the figure it will be seen that the coi
1, 1, are "cut out." Neither of the two halves of
mutator touches the brushes. In this position, how
coils 3, 3, at right angles to 1, 1, are in the positi
action, and the current powerfully induced in them
of the brush marked A (which is, therefore, the negat
into that marked A′. This brush is connected acr
brush marked B, where the current re-enters the
Now, the coils 2, 2 have just left the position of b
and the coils 4, 4 are beginning to approach that
Through both these pairs of coils, therefore, there

partial induction going on. Accordingly, it is arranged that the current on passing into B, splits, part going through coils 2, 2, and part through 4, 4, and re-uniting at the brush B',

FIG. 300.



CONNEXIONS OF BRUSH DYNAMO.

whence the current flows round the coils of the field-magnets to excite them, and then round the external circuit, and back to the brush A. (In some machines it is arranged that the current shall go round the field-magnets, after leaving brush

A', and before entering brush B ; in which case tl
the machine is sometimes, though not correctly, d
causing its coils, as they rotate, to feed the field-n
the external circuit alternately.) The rotation of tl
will then bring coils 2, 2 into the position of least a
they will be cut out, and the same action is renewe
a slight change in the order of operation. The foll
summarises the successive order of connexions du
revolution :—

First position. (Coils 1, 1 cut out.)

$\mathrm{A} - 3 - \mathrm{A}'$; $\mathrm{B}\left\langle\begin{matrix}4\\2\end{matrix}\right\rangle\mathrm{B}'$; Field magnets – Externa

Second position. (Coils 2, 2 cut out.)

$\mathrm{A}\left\langle\begin{matrix}1\\3\end{matrix}\right\rangle\mathrm{A}'$; $\mathrm{B} - 4 - \mathrm{B}'$; Field magnets – Externa

Third position. (Coils 3, 3 cut out.)

$\mathrm{A} - 1 - \mathrm{A}'$; $\mathrm{B}\left\langle\begin{matrix}2\\4\end{matrix}\right\rangle\mathrm{B}'$; Field magnets – External c

Fourth position. (Coils 4, 4 cut out.)

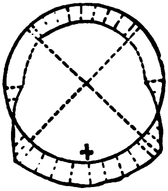
$\mathrm{A}\left\langle\begin{matrix}3\\1\end{matrix}\right\rangle\mathrm{A}'$; $\mathrm{B} - 2 - \mathrm{B}'$; Field magnets – External

From this it will be seen that whichever pai
in the position of best action, is delivering its cu
into the circuit; whilst the two pairs of coils wl
the secondary positions are always joined in
same pair of brushes touching the respective com
both ; and the remaining pair of coils being cut ou

One consequence of the peculiar arrangement t
is, that measuring the potentials round one of
tators with a voltmeter gives a wholly different
that obtained with other machines. For one-ei
circumference on either side of the positive brush
sensible difference of potential. There then con
in which the potential appears to fall off, but th
is here partly due to the shorter time during
adjustable brush connected with the voltmeter an
positive brush are both in contact with the same

tor. Further on there is a region in which the volt-
ves no indications, corresponding to the cut-out posi-
l again, on each side of the negative brush, there is a
here the polarity is the same as that of the negative
'ig. 301 is a diagram of a six-light
ken at one commutator, the main +
ing, however, allowed to rest (as in
position) in contact with both this
tor and the adjacent one.
the foregoing considerations, it will
that the four pairs of coils of the
ichine really constitute four separate
, each delivering alternate currents
nmutator, which commutes them to
ent unidirectional currents in the
and that these independent machines are in-
united in pairs by the device of letting one pair of
oress against the commutators of two pairs of coils.
that these paired machines are then connected in
bringing a connexion round from brush A′ to

FIG. 301.

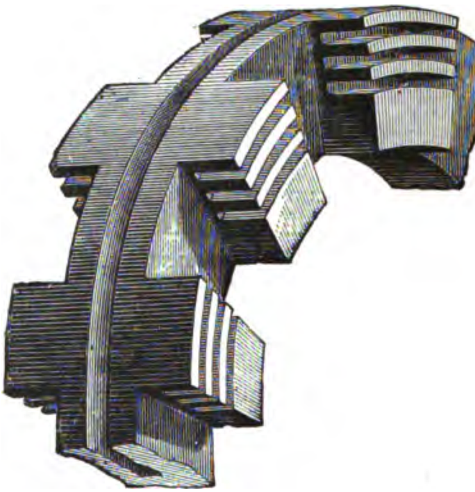


POTENTIALS AT COMMUTATOR OF BRUSH DYNAMO.

core of the Brush ring, as formerly made, was of
cast iron channelled at the sides, so as in some
o obviate eddy currents. The coils are wound in
lial recesses. The form of the ring, with its coils,
discerned in Fig. 297, and the channelled cast-iron
f is shown in Fig. 302. The solid masses of iron in
obsolete form of armature gave rise to wasteful
rrents, the production of which heated the ring and
considerable power. In the newer Brush machines
employed which is built up of a thin iron ribbon
metres thick. Figs. 303 to 305 show its construction,
n reality a larger number of pieces of thinner iron
hown are used. The ribbon is wound upon a circular
on ring A′, projecting cross-pieces of the same
and of the form shown in Fig. 305 (and also
H in Figs. 303 and 304) being inserted at intervals
ate the convolutions, admit of ventilation, and form

suitable projections between which to wind the
the larger armatures there are 45 turns of the rib

FIG. 302.



CORE OF BRUSH RING (Old pattern).

FIG. 303.

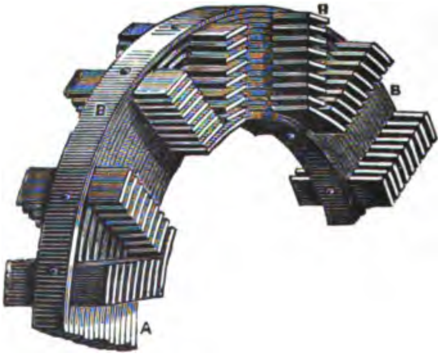


FIG. 304

FIG. 30

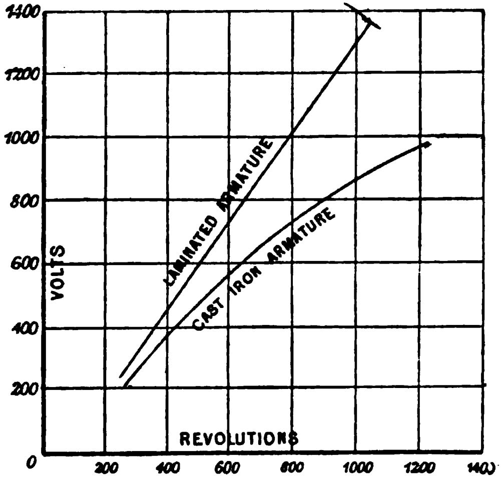
CORE OF BRUSH RING (New pattern).

secured by well-insulated radial bolts. The gain
is great; and the old machine, which formerly
arc lamps, when provided with the new ring
65 lamps at the same speed as before. The sma

machine with an armature of the new type lights 25 lamps, showing that the deleterious reactions have been fairly eliminated; and it may even be run at higher speeds with perfect safety.

The most striking way of realizing the great improvement which has thus been made is to compare the speeds required to develop equal electromotive-forces in the two machines. The experiments were made with identical machines. Both armatures were of the same size, with same length and weight of wire; and the field-magnets were identically excited with a 10-ampere current. The results are shown in the two curves of Fig. 306. At 800 revolutions the old cast-iron armature gave about 730 volts: the new laminated armature gave over 1000 volts.[1]

FIG. 306.



CURVES OF OLD AND NEW PATTERNS OF BRUSH MACHINE.

Some large shunt-wound Brush machines have been recently constructed for electro-metallurgical purposes. The largest of these,[1] having an armature 42 inches in running at 405 revolutions per minute, gave 3200 83 volts. This colossal machine weighs nearly 1 weight of copper on the field-magnets being 5424 the armature 1600 lb. This is at the rate of 1 lb on the armature for every 160 watts of output; for every 1 lb. of copper on the machine.

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[1] **More surprising still, the power absorbed in driving the old armature giving 730 volts was 17 horse-power, whilst that absorbed in driving the new, giving 1020 volts was only 16 horse-power. The old armature could not be run above 800 revolutions per minute without dangerous heating. The new armature may be safely run at a much higher speed, without risk of heating or other danger.**

Some elaborate tests on Brush dynamos, with tw patterns of armature, were made[2] in 1889 by Mr. Melbourne. These showed commercial efficiencie 69·8 per cent. in machines with core-plates 0·05 and of about 78 per cent. in those with core-plates thick. The values of B attained were about 48 magnet cores and 27,000 in the armature cores. T tions of the current were about 1·5 per cent.

Some drawings of a small model Brush dynam in Plate XVI.

The automatic governor used for maintaining the the current is described in Chapter XXVII. on Regulato

Thomson-Houston Dynamo.—This machine, equally remarkable, was designed by Profess Thomson of Lynn and Edwin J. Houston of Philad spherical armature is unique among armatures shaped field-magnets are unique amongst field its three-part commutator is unique among commu general view of the machine is given in Fig. sectional one in Fig. 308. As will be seen from the field-magnet core consists of two flanged iron nished at their inner ends with hollow cups cast i the tubes, and accurately turned to receive the Upon the tubes are wound the coils C C′, and afte two parts are united by means of a number of wr bars *b b*, which constitute the yoke of the magnet same time protect the coils. The magnets are ca framework, which also supports the bearings for th

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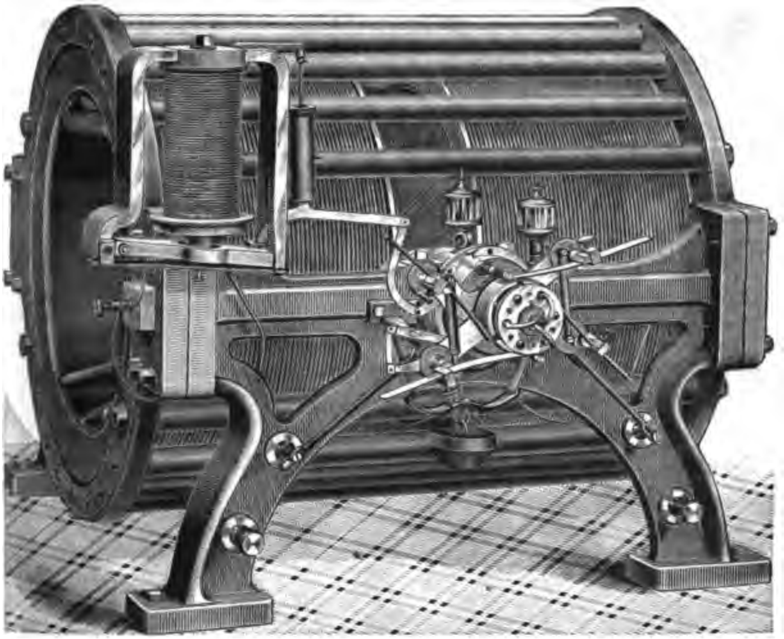
[1] See paper by Prof. Thurston, in *Journal of Franklin Institut* or see *Electrician*, xvii., 469, 1886.

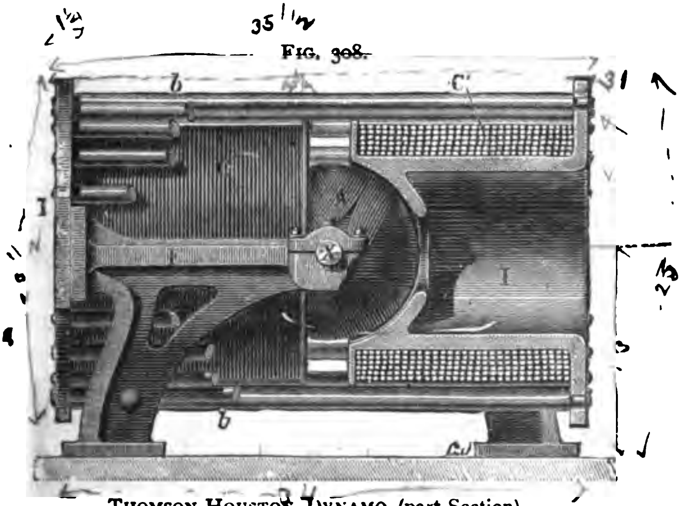
[2] *Journal Inst. Electrical Engineers*, xvii. 710, Nov. 1889.

FIG. 307.



THOMSON-HOUSTON DYNAMO.

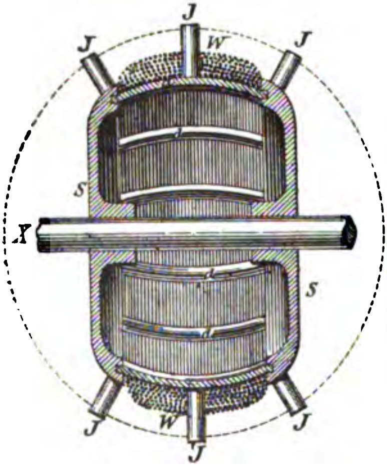
FIG. 308.



THOMSON-HOUSTON DYNAMO (part Section).

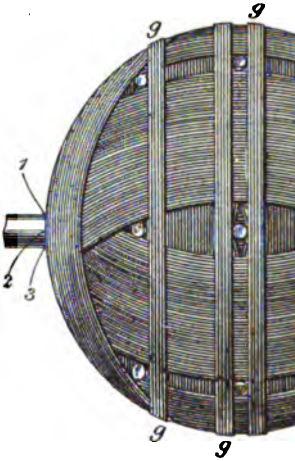
shaft X. The armature, which is spheroidal ra
spherical, is constructed as follows: Upon the shaft
two concave iron disks S, S (Fig. 309), the spac

FIG. 309.



THOMSON-HOUSTON ARMATURE (Section).

FIG. 310.

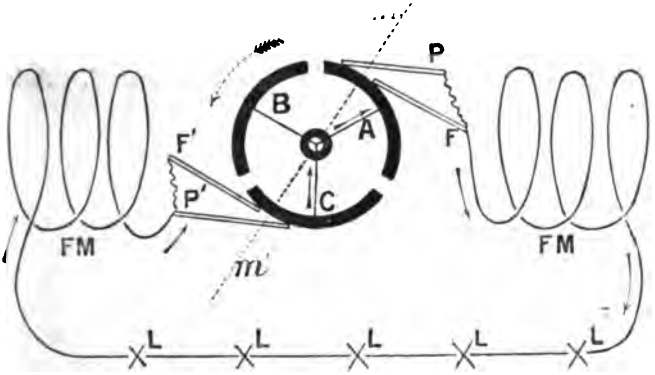


THOMSON-HOUSTON

them being bridged by light ribs of wrought i
Wooden pins J, J, are driven at intervals into a
holes drilled in the iron shell to facilitate the wind
coils. The winding itself is very remarkable. The
three coils. The inner ends of these are united toge
Fig. 307), *and not connected to any other conductor.*
wires are then wound over the shell (which is co
varnished paper) in three sets of windings making
one another, and arranged to be at equal average
from the core by the following device. Beginni
junction at *h*, half the No. 1 coil is wound.
armature is turned through 120° and the No. 2 coil i
to half its length. Then coil No. 3 is wound, sta
h, and finished off at 3. Then the second half c
completed; lastly, the second half of coil No. 1. The
are, therefore, on the average, equidistant from the
their overlapping makes the external form nearly

They are held in place by the binding wires *g g*. Quite recently a new armature has been introduced, also having three coils, but ring-wound so that there is no overlapping. Winding and repairing are thereby much facilitated. The connexions of the three circuits remain as before. When this armature is rotated within the cavity between the cup-shaped poles alternate currents are generated in each separate coil in turn, and it now remains to consider how these alternate inductions are rectified and combined by the commutator. In the diagrams which follow, the rotation is represented as left-handed, as viewed from the commutator-end of the shaft, as it is in practice. Fig. 311 represents the arrangement in diagram. The three coils represented diagrammatically by the three lines A B C, are united at their inner extremities, each outer end being led to one segment of a three-part commutator. There are two positive brushes P and F, and two negative brushes P′ and F′. The current delivered to P and F first flows round one of the field-magnets, thence goes to the outer circuit of lamps, returning through the other field-magnet to P′ and F′. The reader should now compare this diagram with Fig. 292, p. 451, and observe that in that figure the neutral line *n n′* divides the rotation obliquely into two halves,

FIG. 311.



COMMUTATOR AND CIRCUIT OF THOMSON-HOUSTON DYNAMO.

the induced currents flowing outwardly from cent
mutator in all coils that are rising through the
half of this obliquely divided circle; and inwardly
mutator to centre in all coils descending through th
half of the rotation. Accordingly in Fig. 311 there
outward current in A and an inward one in C; I
the moment cut out of circuit as it passes through t
position. Continuity is obtained by the device me
p. 451, of having the second pair of brushes F F′ fol
pair P P′. In this position of the armature A an
about equal angles with the line of maximum ac
hence the two electromotive-forces in these coils
moment about equal, but that in A is increasing,
decreasing. As these coils are now in series, thei
electromotive-forces are of course added together.
later we shall have arrived at the state of things r
in Fig. 312, which is a twelfth of a turn advanced.

FIG. 312.

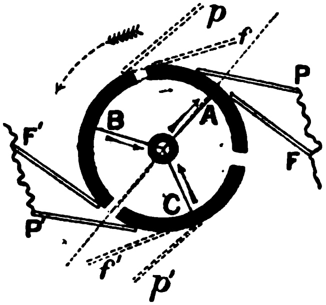
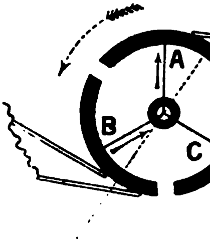


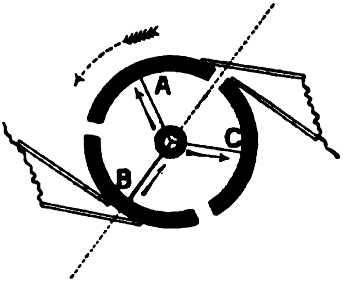
FIG. 313.

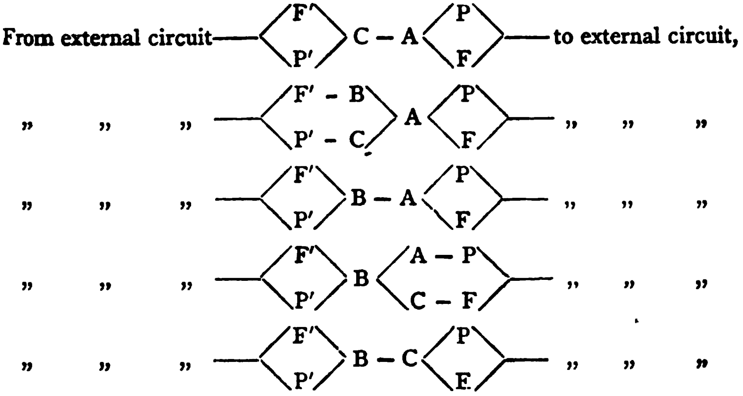


in the position of maximum induction; C is rapidly
ing the neutral postion but is not yet cut out; I
begun to have electromotive-force induced in it, ar
come into circuit. B and C are in parallel with o
and in series with A. The next twelfth of a tur
to the stage shown in Fig. 313. C is now at t
position and is out of circuit, A has passed the ma
one side and B is approaching the maximum on the
they are in series. Another twelfth of a turn an

at Fig. 314. A is fast approaching the neutral position; B is at its maximum; C has passed the neutral stage, and has just come into circuit again by touching the positive following brush. Another instant and C will occupy the place where A was in Fig. 308, a whole third of a revolution having been completed, and the actions recommence, A occupying the place of B, and B that of C. The following table exhibits the round of changes during a third of a revolution:—

Fig. 314.





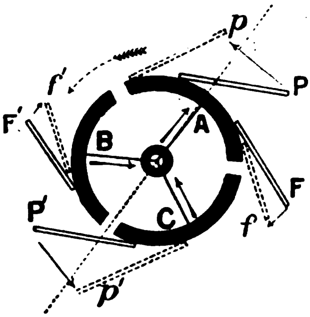
and so forth.

If the width of the gaps between the segments of the commutator be equal to the width between the adjacent brushes, each coil will be out of circuit whenever it is more than 60° from the position of maximum action, and the time during which any two coils are in parallel will be practically nil. But if the following brushes F F′ are at a considerable angle—about 60° in practice—behind the brushes P P′, there will be considerable duration of the stage during which two coils are in parallel.

The regulation of this machine to maintain a constant

current is accomplished by an automatic shifting of t
At first the inventor adopted a method of "forwar
tion, the brushes being set at only 35° in advan
another, and being both shifted forward whenever t
exceeded its proper strength. The effect of this w
by considering the dotted lines *pp′* and *ff′* in
Clearly, if *p* maintained contact with B *after* it h
the neutral line, its electromotive-force would tend t
that of A which is in contact with *f*. This method
in practice unsatisfactory, and has been abando
actual method now used is termed "backward"

FIG. 315.



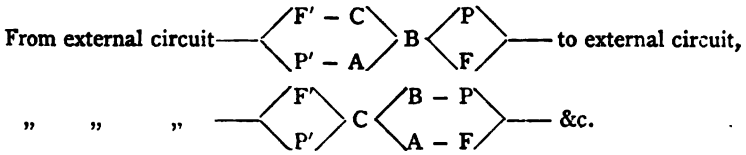
In this system the foll
of brushes F F′ is shi
ward to *ff′* as shown i
whilst at the same time t
brushes P P′ are shifte
through an angle one-thi
towards *pp′*. If, as sta
the brushes are 60° ap
normal conditions, there
actly 120° on either sid
the positive brushes P
negative brushes P′ F′; a
is the exact length of each segment of the comm
coil will be cut out, and parellelism will subsis
two coils through angles of 60°: that is to say,
always be two of the three coils in parallel with o
and in series with the third coil. The six stages
will be :—

From external circuit——⟨F′ – B / P′ – C⟩ A ⟨P / F⟩—— to ext

" " " ——⟨F′ / P′⟩ B ⟨A – P / C – F⟩—— "

" " " ——⟨F′ – A / P′ – B⟩ C ⟨P / F⟩—— "

" " " ——⟨F′ / P′⟩ A ⟨C – P / B – F⟩—— "

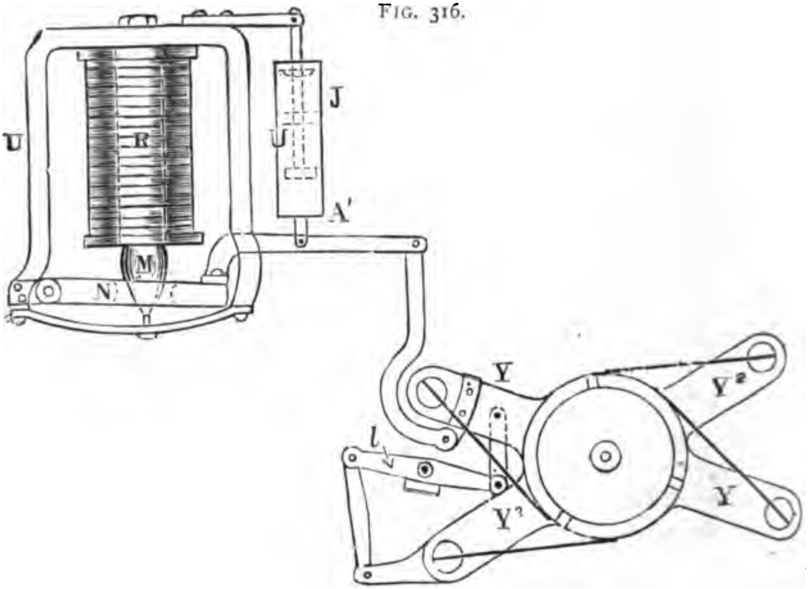


Now suppose the current to become too strong owing to reduction of number of lamps in circuit, the following brushes are made to recede. This will shorten the time during which any single coil in passing through the maximum position is throwing its whole electromotive-force into the circuit, and will hasten the moment when it is put in parallel with a comparatively idle coil. During such movements of regulation the whole machine is momentarily short-circuited six times during each revolution by F receding so far towards P′, and F′ receding so far towards P, as that both touch the same segment of the commutator at one instant. The action is assisted by the slight advance of P and P′, but the main object of this advance is to lessen the sparking. If the current is too weak, then the pairs of brushes must be made to close up, thereby reducing the time during which the most active coils are in parallel with those that are less active.

Regulating Gear.—This motion of advance and retreat is accomplished by the simple mechanism shown in Fig. 313. The brushes are fixed to levers Y Y and $Y_2 Y_2$ united by a third lever *l*. The automatic movement is imparted by the regulating electromagnet R, whose pole M, of paraboloidal form, attracts its armature N according to the current flowing round it. A dash-pot J, attached to the arm A, prevents too sudden motions. The circuits which operate this mechanism are further shown in Fig. 314. Normally the electromagnet R is short-circuited through a by-pass circuit, and only acts when this circuit is opened. At some convenient point of the main circuit two solenoids are introduced, their cores being supported by a spring; and the yoke of the cores operates the contact lever S. If the current becomes too strong this contact is opened, and the regulating magnet R raises the arm A. During running the lever S is continually vibrating up and down, and so altering the brushes to the requirements of the circuit. A carbon shunt of high resistance *r* is added to minimize the destructive spark at S.

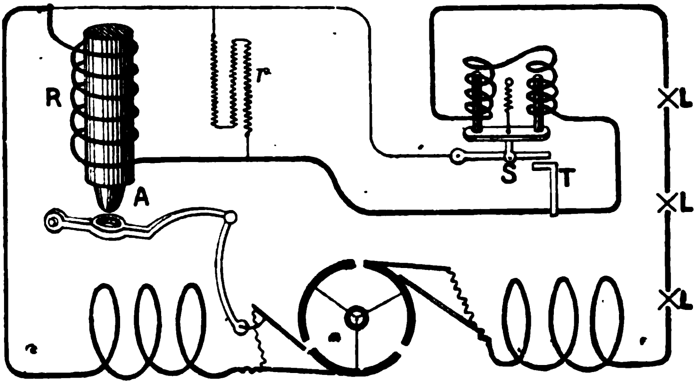
It might be expected that with only three parts to the commutator, the sparks occurring as the segments pass under the brushes would speedily destroy the surface. This difficulty has been met by Prof. Thomson in the boldest manner.

FIG. 316.



REGULATING MAGNET AND GEAR OF THOMSON-HOUSTON SYSTEM.

FIG. 317.



CIRCUITS OF THOMSON-HOUSTON SYSTEM.

By means of a small mechanical blower, fixed upon the shaft behind the commutator, intermittent blasts of air are blown exactly at the right moment so as virtually to blow out the spark. The three segments of the commutator are separated by gaps; and in front of each of the leading brushes (as shown in Fig. 307) there projects a nozzle which discharges a blast, alternately, three times in each revolution.

The normal current for this dynamo is 9·6 amperes, or 6·8 amperes, though they are also wound for stronger currents. One of the larger machines will maintain 63 arc lights in a single circuit, with an electromotive-force of 3000 volts. The ordinary machine supplying 34 arc lamps at 45 to 46 volts each with a current of 9·6 amperes, has an internal resistance of 10·5 ohms in the armature and 10·5 ohms in the field-magnets. The armature is 23⅛ inches in external diameter; its wire being of 0·081 inch gauge. That of the field-magnets is 0·128 inch gauge. The usual speed is 850 revolutions per minute; but the peculiar arrangements for automatic regulation render the machine nearly independent of irregularities in the speed. There is in the armature about 1 yard of wire for every 0·53 volt of the induced electromotive-force. The ratio of weight of copper to iron in these dynamos is very high compared with that of many machines, being 1 of copper to 2·25 of iron.

Professor E. Thomson has also designed, for supplying large currents at low potential, a form of dynamo which is outwardly of similar structure to the machine described above. But in this new machine, which is intended for incandescent lamps in parallel, the spherical armature is wound as a closed-coil in sixteen sections. The field-magnets are much more massive, and the output of the machine more than five times as great in proportion to its size. It is compound-wound; the series coils being wound on a separate frame over the armature.

Advantages of Open-coil Dynamos.—The two great typical open-coil dynamos—those of Brush and of Thomson-Houston—appear to have certain qualities which render them specially applicable as constant-current dynamos for arc-lighting. Three-quarters of all the arc-lights in the world are run by one or other of these machines. It would seem that the

closed-coil dynamos, whether of the ring or of th
are not so well adapted for furnishing the very
motive-forces needed for this work. The commu
many parallel bars insulated with mica or papier-
is the indispensable adjunct of the closed-co
rapidly deteriorates when exposed to the inevita
and wide alterations of lead which are insepara
constant-current method of working. For thi
distribution of electric energy, nothing will st
tear so well as the simple air-insulated commutat
in this chapter. As a partial set-off against thes
may be reckoned the fluctuations in the current
from the employment of so few coils or groups o

Fluctuations of Current in Open-coil Arm
calculations of the fluctuation given in Chapter I
closed-coil armatures are also applicable to op
tures, provided there is no cutting out of coils.
coils are cut out, the fluctuations are less ma
calculations are less simple. That such fluctua
abundantly verified by the interference of arc-
with neighbouring telephone lines in which
buzzing noises. Rapidly fluctuating currents a
the self-induction of any electromagnets in the
always tends to tone down the rapid fluctuations
the current.

A special study of the curves of induction in
of a Thomson-Houston arc-light machine has be
Mr. Milton E. Thompson, who found the total c
load to fluctuate between five and eight amperes
each revolution; the mean current being 6·8.
tions of electromotive-force in each individu
very remarkable; the curves being singularly irr
to near zero twelve times in each revolution.

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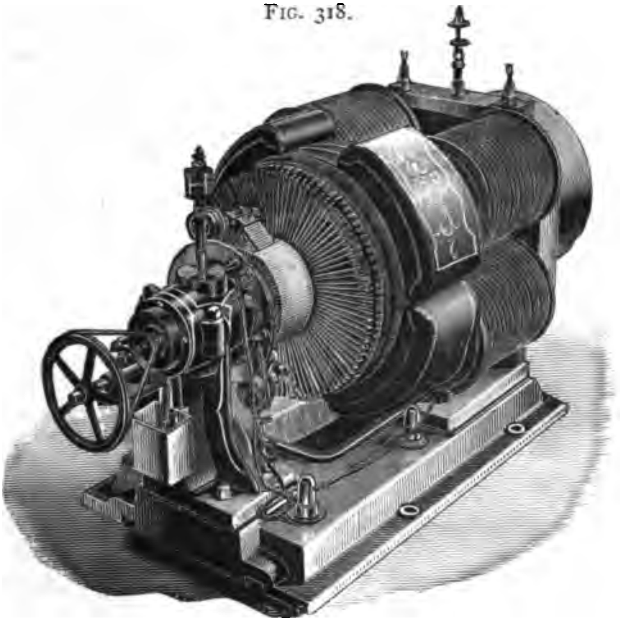
[1] *Electrical World*, xvii. 392, 1891, and *Electrical Review*, x

OTHER ARC-LIGHT MACHINES.

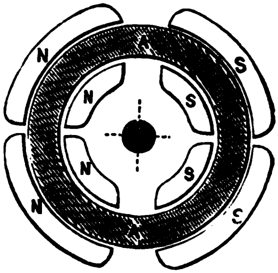
Sperry's Dynamo.—An arc-light dynamo with a Gramme armature is that of Sperry, Figs. 318, 319, the distinguishing feature of which is the use of internal as well as external pole-pieces. One of these machines, shown, in 1889, at Paris, gave ten amperes at 620 volts, when running at 1000 revolutions per minute. The ring-core was of $10\frac{9}{16}$ inches internal and $13\frac{1}{2}$ inches external diameter, and $6\frac{1}{4}$ inches long. The commutator had 72 bars; and the winding consisted of 72 sections of 40 turns each in four layers. The clearance space outside the binding wires was about $\frac{5}{32}$ inch. The inventor claims[1]

FIG. 318.



SPERRY'S ARC-LIGHT DYNAMO.

FIG. 319.



SECTION OF SPERRY DYNAMO.

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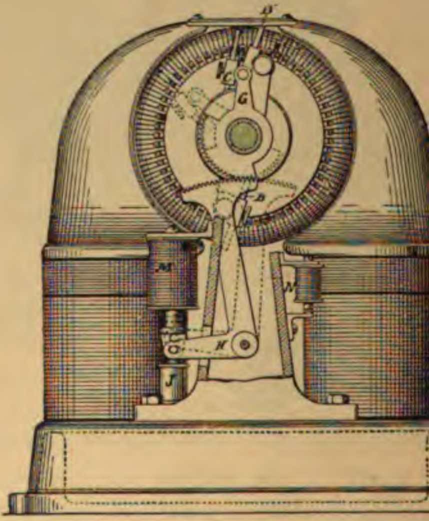
[1] See appendix to paper by Esson, in *Journal Inst. Electrical Engineers*, xix. 157, 1890.

that the brushes may be advanced from the
electromotive-force to even a position of zero
sparking; the cross-magnetizing action of the
small compared with the power of the field-ma

Wood's Dynamo.—This also is a mod
machine,[1] supplying 9·6 amperes at 2640 vo
of 875 revolutions per minute. There are 12
72 turns in each, and a cross-section of iron

FIG. 320.



WOOD'S DYNAMO.

14 sq. inches. To obviate sparking, there i
brush placed 5 to 10 sections ahead of the co
and the voltage is varied by a device which sh
forward. The largest arc-lighting station in th
St. Louis, Missouri, is supplied with 53 of
each capable of feeding 60 arc lamps.

Ball's Dynamo.—For ten years there has b
used in the United States a machine having

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[1] See *Electrical World*, xii. April 23, 1887, and xiv. 54
xvii. 4, 1891.

armatures side by side on one shaft, with a magnetic circuit of very singular design. To each armature there is only one pole-piece, so that the magnetic lines which enter the ring on one side have to find their way out across a wide irregular gap, with the consequence that there is great magnetic leakage and waste of magnetizing power. The disadvantage of this method of using a bad magnetic circuit was pointed out in the earlier editions of this work; and experiments were cited showing how, with a rational arrangement to magnetize one armature between two pole-pieces instead of half magnetizing two armatures with one pole-piece each, a single armature might yield as high an electromotive-force as do the two. It remains, however, to be stated that in spite of these imperfections of design, the Ball machine has given great satisfaction, its construction having been evidently carried out with good engineering skill.

Edison's Municipal Dynamo.—A special machine for series lighting, by means of incandescent lamps, is used by the Edison Company under this name.[1] There are several sizes of machine for currents of 9, 16, 32, and 48 amperes respectively. The smallest of these has three circuits, each to supply a three-ampere current to a separate row of lamps, the volts being 1200 at 1600 revolutions per minute.

Phœnix Arc Dynamo.—Mr. W. B. Esson has designed arc-light dynamos[2] for Messrs. Paterson and Cooper, using Gramme ring armatures; and finds no difficulty in constructing them from 800 up to 1500 volts. Some are of the form shown in Plate V., but are wound somewhat differently for constant-current work; others have a double magnetic circuit. As the armature is wound with many turns of fine wire, there are many turns to each section, which therefore possesses considerable self-induction, and requires a large electromotive-force to reverse the current in it in the act of commutation. If, therefore, the regulation is to be effected by shifting forward the brushes, it is clear that in every position, from minimum to maximum of the range, the magnetic field in the gap must be adequate ; and as the coefficient of self-induction is nearly constant, the field in the gap-space must also be nearly constant. In other words, the iron of the field-magnet may be reduced in quantity, but excited to a high degree, so as to be more constant in its magnetization.

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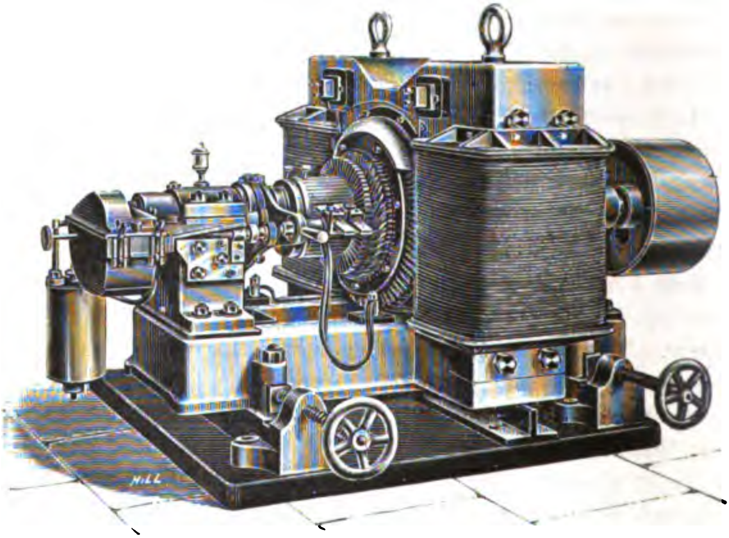
[1] *Electrical Review*, xxv. 209, 1889.

[2] *Journal Inst. Electrical Engineers*, xix. 161, 1890.

Statter's Dynamo.—Another example of a constant-current dynamo, with an automatic regulator to shift the brushes, is afforded by Statter's machine, in which, by a careful shaping of the pole-faces, a disposition of the magnetic field is obtained which permits the machine to run sparklessly. The mechanism which moves the brushes consists[1] of a toothed wheel, actuated by one or other of two pawls driven from the shaft by an eccentric. A solenoid in the main circuit controls the action of the pawls, and so shifts the brushes forward or back as may be needed to keep the current constant.

FIG. 321.



STATTER'S CONSTANT CURRENT DYNAMO.

Schuyler's Dynamo.—This machine has a drum armature wound in eight parts, and coupled up so that the coils are successively cut out at the neutral points.

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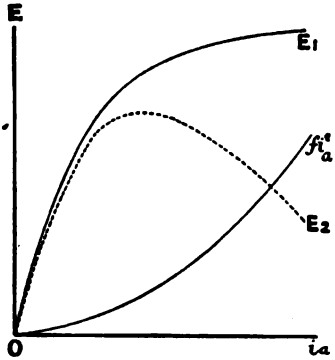
[1] *La Lumière Électrique*, xxx. 321, 1889; and Specification of Patent, 2825 of 1887.

Other Open-coil Dynamos.—Other forms of open-coil dynamos have been proposed by Bain, by Newton, and by Dr. Hammerl. The armature of the latter consists of a Gramme ring wound in sections, but having the inner ends of all the sections united together at a common junction, and their outer ends brought each to a separate bar of a collector. Sir Wm. Thomson has also suggested other forms in one of which the armature resembles a bicycle wheel. A disk dynamo of kindred design has lately been constructed by Poleschko, and is described in Chapter XIX.

Drooping Characteristics.—A method which, though not in itself securing constancy of current, is much followed in the construction of arc-lighting dynamos, should here be explained. Attention was drawn on p. 256 to the drooping form of the characteristics of certain series-wound machines. It is obvious that if this effect is sufficiently exaggerated, the drooping portion of the characteristic will correspond to the case of an approximately constant current. The drooping characteristic is important in promoting the steady working of arc lamps in the circuit. Suppose an arc lamp to be running on a series-wound dynamo under such conditions of working that the characteristic is ascending, any shortening of the arc will be followed by a reduction of resistance and a large increase of current. Whereas if the conditions of working are such as to fit to a point on the drooping part of the characteristic, any decrease in resistance in the circuit will result in a comparatively small increase of current.

The causes that tend to cause the characteristic of the series dynamo to turn down after reaching a maximum height are: (1) the demagnetizing effect of the armature current when there is a positive lead at the brushes; (2) the saturating of the iron of the armature core before that of the field-magnets; (3) the leakage of magnetic lines from the field-magnet; (4) the peculiar commuting arrangements in certain machines—for example, the open-coil dynamos mentioned previously—which make their effective electromotive-force vary greatly with the position given to the brushes; (5) high internal resistance, and self-induction. As the demagnetizing effect of the armature current is nearly proportional to the strength of the current and to the sine of the angle of lead, and as the sine of the angle of lead is itself nearly proportional to the armature current, it follows that the whole demagnetizing effect is nearly proportional to the square of the armature current. In Fig. 322 let the curve E_1 represent the electromotive-force (at a given speed) when the field-magnets are separately excited, the armature circuit being left open; this includes the effect of (2) and partially (3) above. On the same diagram a curve having ordinates proportional to i_a^2, and of such a magnitude as to represent the demagnetizing action of the armature current, may be plotted. Deducting the ordinates of this curve from those of curve E we get curve E_2, the drooping characteristic. The trouble with all machines of this class is the sparking at the brushes consequent on the variability of the angle of lead.

FIG. 322.



The effect of a drooping characteristic can to some extent be obtained by inserting in the external circuit a resistance of from 1 to 2 ohms. And this is preferable to having an internal resistance that would add to the heating of the armature. But such auxiliary resistance should be coiled on an iron core, since self-induction here is of value in steadying the current.

Constant Current Regulators.—A number of devices applicable to arc-light dynamos are described in Chapter XXVII.; amongst them being the "third-brush" regulator of Waterhouse for use in arc lighting.

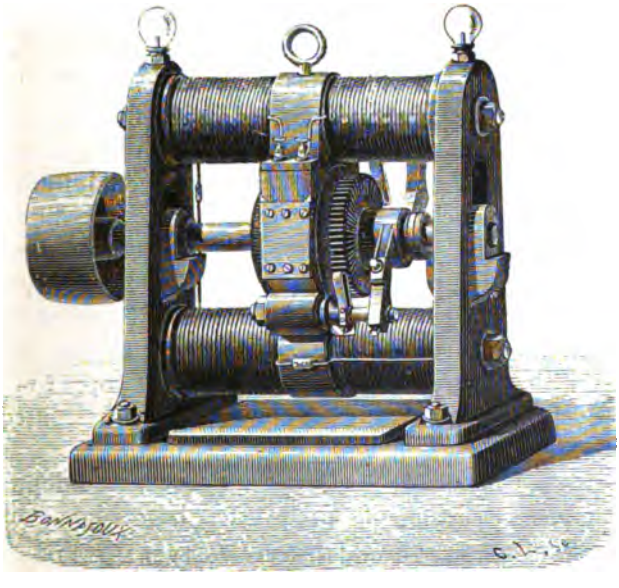
CHAPTER XVIII.

EXAMPLES OF MODERN DYNAMOS.—(Direct current.)

GRAMME DYNAMOS.

INNUMERABLE forms have been given to the Gramme machine at different dates since its appearance in 1871, varying from small laboratory machines with permanent steel magnets, such as are shown in Fig. 323, to large machines absorbing 30 or 40 horse-power. Those who desire more detailed information concerning the various patterns of Gramme dynamo should consult the earlier editions of this

FIG. 323.



GRAMME DYNAMO, "A" PATTERN.

work, in which a number of forms[1] were de
should also refer to the treatise of the late M
entitled *Machines électriques à courants con*
Gramme et congénères (1881). Fig. 323 shows th
Gramme, the first pattern which came into comr
which, with little alteration save general streng
design, is in extended use to-day. Its charac
are the ring-armature, made of an iron wire
overwound with coils (described p. 343), and the
field-magnet having consequent poles, a dou
above, and a double south pole below the ar
ring depicted in Fig. 35 (p. 43), is of more
struction, better built than the original type, an
the shaft by an internal gun-metal spider, in
driven on to a wooden hub; and the collecto
vented from flying to pieces by the addition o
ring shrunk on over their ends.

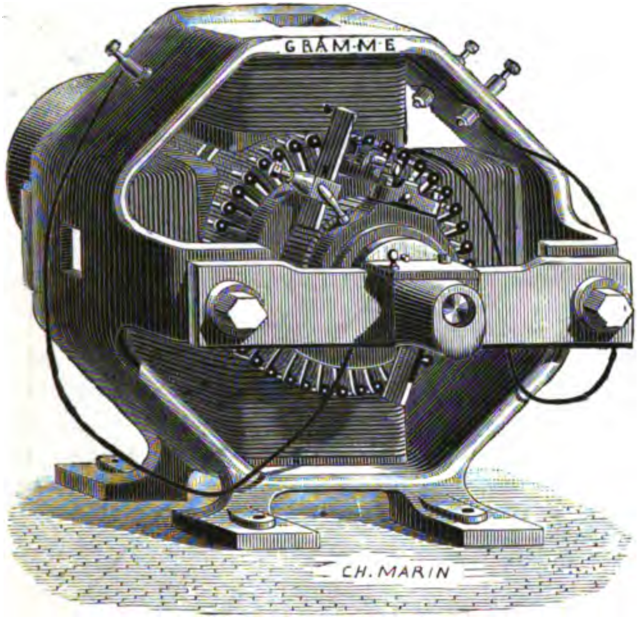
Another more recent form of Gramme d
depicted in Fig. 324, which has four *salient*
tinguished from the consequent poles at the m
the electromagnets. The field-magnets of thi
simple, for the four cores, the external octago
one of the two brackets which carry the shaft,
one piece (Fig. 324). The object of this is to
light, and portable machine suitable for temp
The coils are wound on a separate mould, and
secured in their places. Some of these mac
structed with two poles only. The weight of
is relatively less than in the machines wi
poles.

In 1885 a new form of field-magnet wa
M. Gramme, consisting of an inverted horse

---

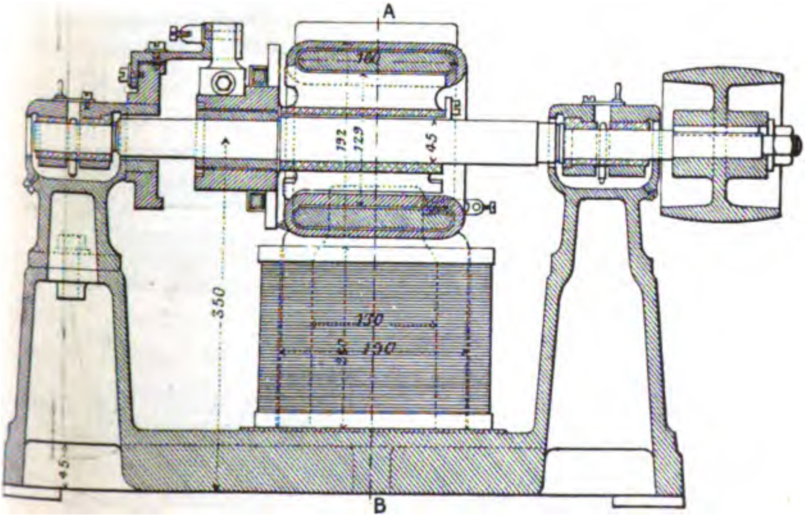
[1] Amongst these are the improved forms designed by M. M
designed by Mr. Hochhausen, and those made by the Fulle
York; Mr. Wood of New York, has also perfected the desi
Other modifications have been made by M. Raffard, by MM.
and Co., and by other French engineers: of these, some
Industries, Nov. 5th, 1886. For an account of Gramme's hist
Paris Exposition of 1889, see *Industries*, vii., 285, 1889.

FIG. 324.



FOUR-POLE GRAMME DYNAMO (1885).

FIG. 325.



GRAMME DYNAMO (*Type Supérieur*, 1885).

FIG 327

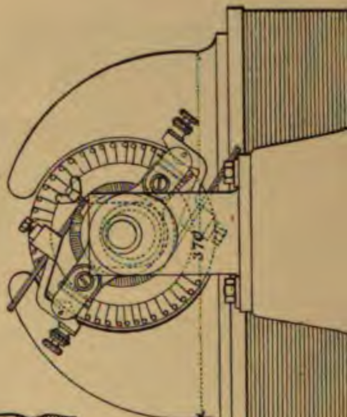


FIG. 328.

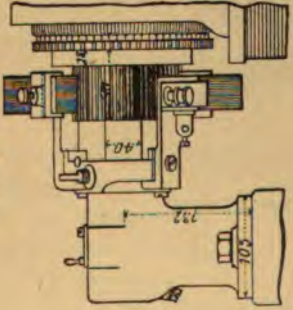
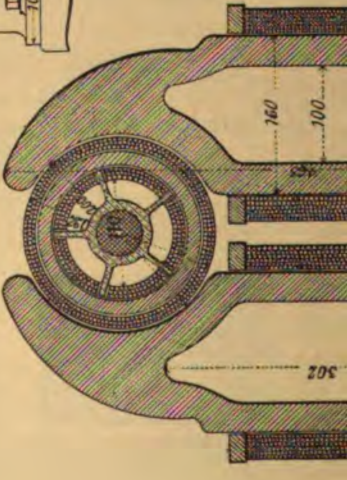


FIG. 326.



machine, sketches of which are given in Figs. 325–8, the bed-plate, the magnet-cores, the pole-pieces, and the supports of the bearings are of cast iron, all in one piece.

The field-magnet coils are wound on separate mandrils and then slipped over the cores between cheeks of insulating substance. The ring-armature is driven upon a spider of bronze, keyed to the shaft, its outer edges passing between the insulated copper coils and supporting the core, which is of laminated iron. The collector bars are held together by an external ring of bronze, well insulated from them. The details are shown in the figures, and it will be noted that the field-magnet cores are for some reason cast hollow. Fig. 328 shows the arrangements of the brush-holders. One of these machines, intended for an output of 40 amperes with a pressure of 110 volts, at a speed of 1400 revolutions per minute, had the following dimensions :—

Internal radius of armature core, 6·5 cm. ; external radius, 9·15 cm. ; axial length of core, 16 cm. ; total sectional area of armature core, 80 sq. cm. ; distance from armature core to pole-piece, 0·85 cm. ; estimated area of each polar surface, 366 sq. cm. ; sectional area of each iron magnet core, 174 sq. cm. ; estimated length of magnetic circuit within field-magnet, 81 cm. ; commutator-bars, 60 ; total number of windings on the ring, 300 ; armature resistance, 0·174 ohm ; shunt resistance, 46 ohms.

CROMPTON'S DYNAMOS.

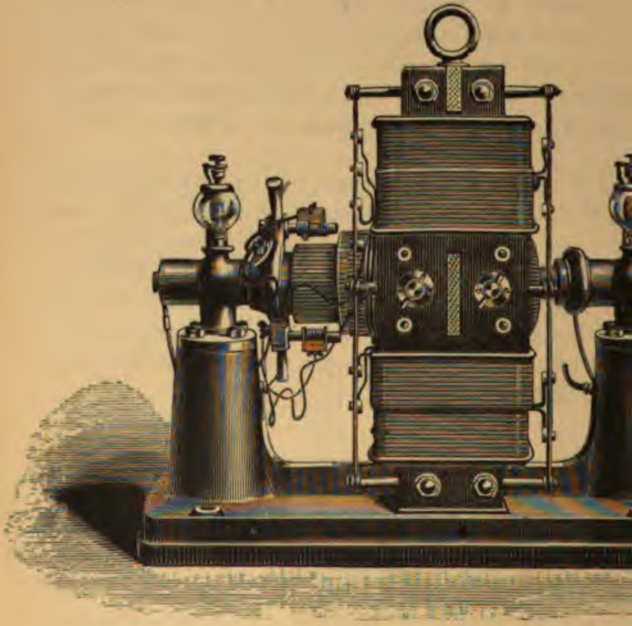
Mr. R. E. Crompton, who pioneered many of the improvements in recent years, began with the now obsolete Bürgin form of ring-armature, for which, with the collaboration of Mr. Kapp, he subsequently adopted the cylindrical rings described on p. 349.

A general view of the Crompton dynamo is given in Fig. 329, which shows vertical field-magnets with a double magnetic circuit.

The armature windings, in the 1887 type, are formed of specially drawn copper wire of nearly rectangular section, cotton-covered, there being one turn of such wire to each segment of the commutator. The separate turns are bent to shape on proper formers before being placed on the ring, and

are taped together in twos, so that when put in
with the longer dimension of their rectangular
so getting great depth of copper radially on
The two turns lie side by side on the externa
the ring, but radially above one another at
periphery. The armatures are usually providec
projections of insulated metal, inserted at inte

FIG. 329.



CROMPTON'S DYNAMO (1887).

the conducting wires; and after winding are st
with binding-wires of tinned steel. In some
recent machines a single magnetic circuit only
Another improvement useful in machines for fu
currents consists in dividing each conductor on
periphery of the armature into two or more str
crossed under one another at the middle and un
at their ends. Instead of such imbricated strip

bars of compressed stranded wires are now used in all large output machines. This construction greatly diminishes the eddy-currents which are set up in the conductors if they consist of single rods or bars.

A complete account of Mr. Crompton's successive stages of improvements[1] would occupy a volume in itself. Besides the improvements made in conjunction with Mr. Kapp on general design, p. 349, and more favourable use of iron in the armature, a number were made in conjunction with Mr. Swinburne on various modes of winding, p. 367, and on machines with conductors embedded in the core-disks. Then Mr. Crompton found that it was needless to insulate core-disks from spindle if they were separated from one another throughout their surfaces up to the periphery. Next came the question of driving-teeth, and the thick driving-disks mentioned on p. 349 were abandoned in favour of teeth of delta-metal or aluminium bronze, fitted into the substance of the compressed core. Then came the production of imbricated and compressed stranded conductors to obviate eddy-currents. Lastly, the adoption of multipolar series windings for drum armatures. With large four-pole machines for central-station lighting Messrs. R. E. Crompton and Co. have had great success. The construction of some of their large-output armatures is indicated in Figs. 265 and 266, on p. 370.

KAPP'S DYNAMOS.

Mr. Gisbert Kapp has designed various forms of direct-current dynamos, some having cylindrical ring-armatures, the more recent ones drum-wound armatures. The latest and best construction of 2-pole machine is that depicted in Fig. 330, being of the "over" type with the armature and shaft at the summit of the field-magnet. These machines are constructed by Messrs. W. H. Allen and Co., and by Messrs.

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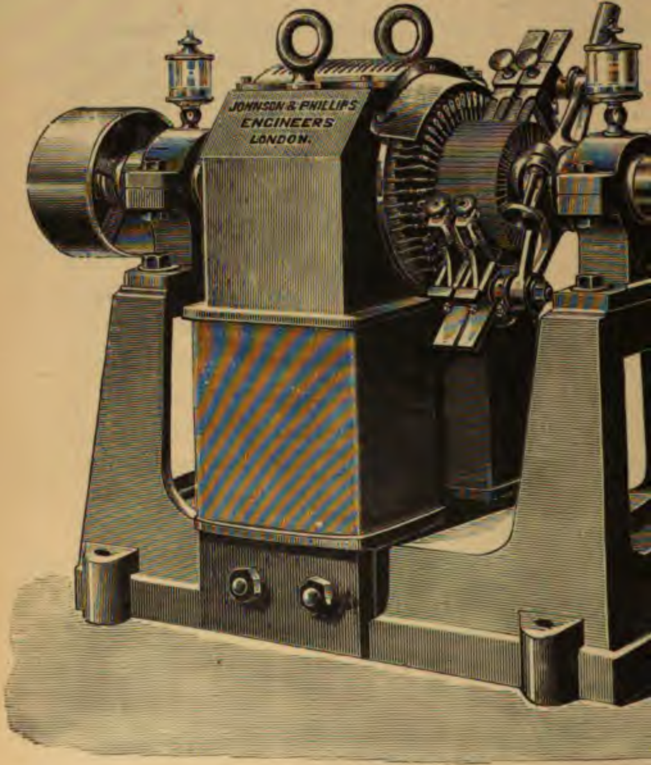
[1] See remarks by Mr. Crompton in *Proc. Inst. Civil Engineers*, lxxxiii. 125, 1885; *Journal Soc. Teleg. Engineers*, xv. 546, 1886; and *Journal Inst. Elec. Engineers*, xix. 239, 1890, and xx. 308, 1891.

Johnson and Phillips. In Plates I., II., and I
drawings of a 21-unit machine by the latter fir

FIG. 330.



KAPP DYNAMO.

amperes at 105 volts at 780 revolutions per m
following are the data of this machine:—

Armature. Core 16″ long by $2\frac{3}{8}''$ deep, mounte
spider. Area of iron in core, allowing for insulation
disks, 62·5 sq. in. External diameter $11\frac{1}{32}''$. Conduc
bars, each made of two parallel bars, 0·208″ × 0·11
united in parallel, affording 0·046 sq. in. sectional area
120 copper semicircles with lugs; depth $1\frac{5}{8}''$; thick
Resistance (warm) 0·025 ohm. Commutator 60 parts

Field-magnets. Diameter of bore, $11\frac{15}{16}''$. Shunt win
of 139 turns each, of 0·065″ diameter round copper wi

a diameter of 0·080″, on each limb, and the two limbs connected in series. Total shunt turns 3058. Series winding 23 turns on each limb, of copper tape, 0·480″ wide by 0·130″ thick, and the two limbs joined in parallel. Resistance of shunt coils (warm) 30·8 ohms; of series winding 0·0079 ohm.

One peculiarity in this dynamo is the mode of driving the conductors of the armature. As shown in the section in Plate II., there are introduced at intervals between the core-disks, some thicker disks having ventilating apertures and projecting horns of steel. Around these steel horns are placed pieces of hard white fibre, as driving-horns; and as these project in alternate positions, the copper conductors cannot be laid straight, but are given a sinuous form. Plate II. also shows how the core-disks are clamped together by face-plates having ventilating perforations through them, the whole core being held up against a collar on the shaft by a screw-nut. The figures in Plates I., II., and III. also show the details of the brush-holder and rocker, the construction of the field-magnet, the arrangements of the bearings, and the pattern of lubricator employed.

Kapp's Multipolar Drum Dynamo for central-station lighting is shown on Plate IX., Fig. 2. This is a 6-pole machine with the armature windings grouped in parallel, or, if desired, in series, so as to need but two sets of brushes. The windings are of a cable of stranded insulated wire. The following are the data of the machine depicted :—

Ouput. 1100 amperes at 50 to 55 volts, at 460 revolutions per minute.

Armature. Length 12 inches; diameter 24 inches; number ot conductors 224, connected in parallel grouping for six poles; nett armature resistance from brush to brush 0·00166 ohm (warm); commutator 112 segments; six sets of brushes at 60° apart.

Field-magnets. Cores, circular, 9 inches in diameter; pole-pieces 11¼ by 10 inches; exciting ampere-turns 8000 per magnet core.

A still larger 8-pole dynamo, having output of 134 kilowatts, is to be shown at the Crystal Palace. In this dynamo the pole-pieces are bevelled off only at the edge of pole-surface where the conductors approach the pole.

BROWN'S DYNAMOS.

These excellent machines, made hitherto at
Machine Works, near Zürich, are of several typ
illustrations are given in Plates IV., VIII., IX.,

PLATE IV. *Glow-lamp Dynamo,* 28 *kilow*
400 amperes at 70 volts; 38 HP. at 400 r
minute. This machine resembles the "Man
but is even more massive, and is now mad
instead of ring winding. The core-disks a
long sleeve, and they are pierced to receive th
ductors; the perforations being 12 mm. in d
1 mm. below the periphery. The thickness
space from iron to iron is thus reduced to 2·
disks, external diameter 51·4 cm., internal di
thickness 0·6 mm.; number 570, insulated with
sectional area of iron in armature 480 sq. cm.
conductors around periphery, 80; commuta
resistance of armature, brush to brush, 0·00525
magnets, shunt wound with 2800 windings of
diameter; resistance 6 ohms, with about 1
series for regulation at above speed and output
passing through holes in armature are round co
in diameter. The end-connectors are of strip
legged pieces bent into spiral shape.

PLATE VIII. *Four-pole Ring Dynamo for*
of Power, 170 *kilowatt dynamo.*—Output 27
625 volts; 240 HP. at 500 revolutions per m
machines, of which two were shown in the Par
of 1889, stand nearly 8 feet high. They ar
with the windings external to the core-disks, as
tion with conductors embedded in perforations
for machines exceeding 100 volts. The cast
are arranged radially, and are united by a very
ring, the lower half of which is cast in one
frame and the supports for the bearings. Th
96 cm. in diameter, and 50 cm. deep. Core-
diameter 66 cm., external diameter 96 cm., thick

insulated with paper; net sectional area of iron in ring 660 sq. cm.; gap-space, iron to iron, 16 mm.; winding (generator) 400 turns of cable containing 19 strands of 1·3 mm. wire, wound in one layer externally and two layers internally; resistance, brush to brush, 0·025 ohm; cross-connexions, none; commutator 200 parts. Field-magnet coils in series with armature, and are each wound with 60 turns of 1 mm. copper sheet 30 cm. in width. Weights are as follows:—Frame and magnet cores 11,600 kilos., armature iron 1430, armature copper 132, armature complete 2420, magnet copper 1370. Total weight of complete machine, 15,700 kilos, or nearly 16 tons. At 500 revolutions per minute, it can be run at 250 HP. continuously night and day. If run in day only the current may be increased so as to work at 300 HP. Commercial efficiency at full load 93—94 per cent.

The machine used as motor, with the above generator, is nearly identical, the only differences being that there is slightly less iron in the armature, and there are only 364 windings with a 184-part commutator. Modified in this way the speed is constant, though the loss in the line varies with the load. Experience, which has dictated this proportion, leads, in this case, to the rule that for the motor the armature should be relatively less powerful, and the field-magnet relatively more powerful than in a generator.

A general view of this same machine is given in Plate IX., Fig. 1.

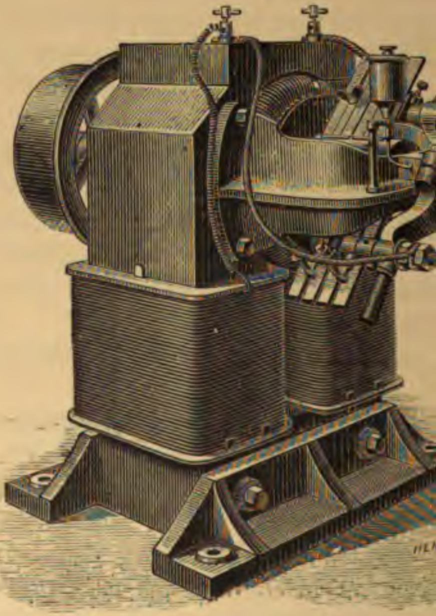
PLATE X. *Eight-pole Ring Dynamo for Electro-metallurgical Purposes.*—For the use of the aluminium industry Mr. Brown has produced 6-pole and 8-pole dynamos. That depicted in Plate X is a 300 HP. machine, working in the aluminium establishment at Neuhausen. It is fixed with its shaft vertical in continuation with the shaft of a vertical turbine. After working continuously day and night, with an average output of 3000 amperes, the commutator remains polished, for the machine runs sparklessly. The mode of cross-connecting each part of the ring winding to the two points of the commutator 45° distant is accomplished by bent two-legged strips of copper, as shown.

PATERSON AND COOPER'S DYNA

The "Phœnix" dynamo, constructed by M and Cooper, from the designs of Mr. W. B. Es modified cylindrical ring armature, built up very thin rings of Swedish iron separated fro by paraffined paper and secured to two spiders passing through indentations in the core-ring Fig. 245, p. 348.

There are no transverse gaps in the arm lation, as there is little heating in this arm

FIG. 331.



PHŒNIX DYNAMO (1887 Wrought-iron Ty

machines originally had a field-magnet with d circuit of forged iron and toothed core-ring machine shown at the Antwerp Exhibition (o

372 watts per pound of copper, and 1·31 volts per yard of coil.

The latter machines have upright single horse-shoe magnets, in some instances made of a single wrought-iron forging slotted out to form the two limbs, and bored, as shown in Fig. 331. The shaft is supported from two gun-metal bridge-pieces. There are generally no teeth on the armature-cores, which are made of plain washers to avoid cost of milling out the teeth.

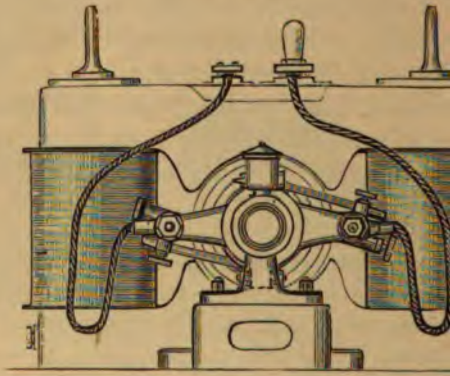
The following particulars of this machine have been furnished by the makers:—

The 25 kilowatt machine is designed for an output of 100 amperes at 250 volts pressure, when driven at 700 revolutions per minute. The total weight is 3136 lbs.; the useful output being 8 watts per pound of material. The external diameter of the armature core is 34·6 cm.; internal diameter of armature core, 20 cm.; length of armature core, 30 cm.; cross-section of magnets, 30 cm. by 20 cm.; nett sectional area of iron in armature, allowing for insulation, 193 sq. cm.; sectional area of iron in field, allowing for rounded corners, 612·7 sq. cm.; diameter of polar cavity, 37·5 cm. The armature is wound with 360 turns of 3·75 mm. square wire in two layers. The field is shunt wound, each limb containing 3540 turns of 1·55 mm. wire, and the total resistance is 83 ohms. The radiating surface of both magnet limbs is 7740 sq. cm., and the energy used in exciting is 750 watts; the ratio of the cooling surface being therefore 10·3 sq. cm. per watt.

From the above data we find that the total number of magnetic lines that cross the armature is about 6,200,000, and that the useful induction through the armature is 16,000, and the induction through the field 10,100 lines per sq. cm. The peripheral speed of the armature core is 2530 feet per minute, and the total length of conductor wound on the armature is 11,200 inches, being at the rate of 45 inches per volt in the external circuit. At a peripheral speed of 3000 feet (which is a fair average in modern belt-driven dynamos), 38 inches of armature conductor would produce 1 volt. In larger machines for heavy output of current, the makers have for six or seven years past used a stranded cable as conductor for the armature. This construction, which nearly all makers now follow, obviates eddy-currents which would arise in solid bars.

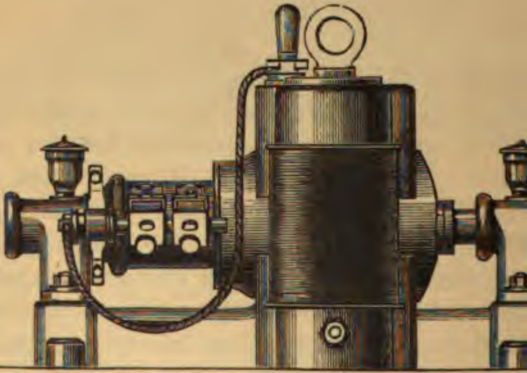
19·36 ohms; series coil, 0·012 ohm. With a
revolutions per minute the current was 22

FIG. 333.



MATHER AND HOPKINSON'S DYNAMO (End Ele

FIG. 334.



MATHER AND HOPKINSON'S DYNAMO (Front El

machine being nearly self-regulating for
efficiency is 90·9 per cent.[1]

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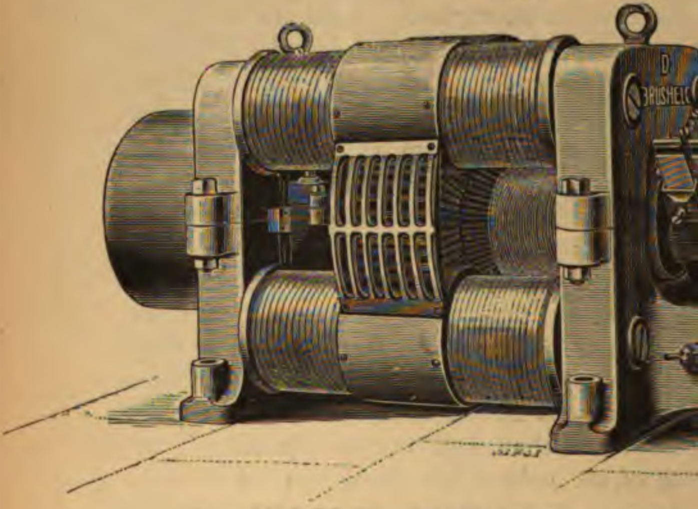
[1] One of these machines is very fully described in the pape
Hopkinson in the *Phil. Trans.* for 1886.

"VICTORIA" (BRUSH CO.'S) DYNAMOS.

The Brush Electrical Engineering Co. has produced a dynamo of the flat-ring type, under the patents of Schuckert, Mordey, Wynne, and Sellon, to which the not very apt name of the "Victoria" dynamo has been given. There are two types of this dynamo, one having four, the other six poles arranged round the ring. The development of the Victoria machine from the original Schuckert machine commenced, under the auspices of the electricians of the Brush Company, with the discovery by Mr. Mordey, by the aid of his method of examining the distribution of potentials round collectors, that there was in the machine a point at a considerable distance in front of each brush, having the same potential as the brush, and that the whole of the portions of the armature between these equipotential points were useless, or worse than useless, as they were occupied only in producing an opposing electromotive-force. In some of the early Schuckert dynamos these useless portions occupied more than half of the armature. By reducing the size of the pole-pieces, space was found for a 4-pole field, the effect of the change being that, from the same ring as employed by Schuckert with a 2-pole field, the electrical output was doubled, without increase of speed. Great attention has been given to the form of the pole-pieces. These pole-pieces in the earlier Schuckert machines, consisted, as mentioned above, of hollow iron shoes or cases which occupied a large angular breadth along the circumference of the ring. Similar hollow polar extensions were long used in the Gülcher machines. By long extended experiments Mr. Mordey arrived at a narrower form of pole-piece, not covering more than 30° of angular breadth of the circumference of the armature, which completely obviated these effects. As will be seen from Fig. 335, which represents the 4-pole Victoria dynamo as now constructed, the pole-pieces, though they embrace the ring through its whole depth, from external to internal periphery, are not quite so narrow. This has been rendered possible by changes in the proportions of

the dynamos, which have reduced the inductiv
armature. The pole-pieces are of cast iron sh
cylindrical cores of soft wrought iron which re
The armature of the Victoria dynamo has

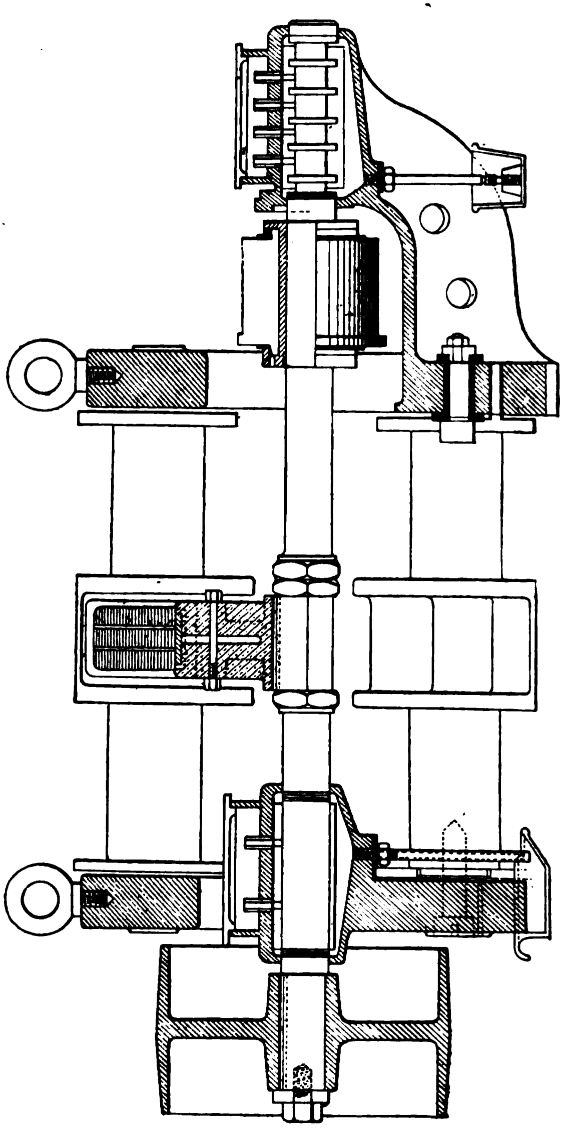
FIG. 335.



VICTORIA (SCHUCKERT-MORDEY) DYNAMO OF BRUS
ENGINEERING CO.

been modified, and its core is now made of
section. It is built up of charcoal iron tape,
strong foundation ring, contact between suc
being prevented by coiling paper between.
have been taken throughout to ensure that
electric circuits made in the bolting together o
each layer being insulated from the adjacent l
currents in the core are thus almost entirely o
foundation ring and some of the inner convoluti
slotted out to receive the gun-metal arms, of w
two sets clamped together, one on either si
shows this construction and the method of se
to the shaft by lock-nuts. Square wire is use
the armature coils, and as they do not co

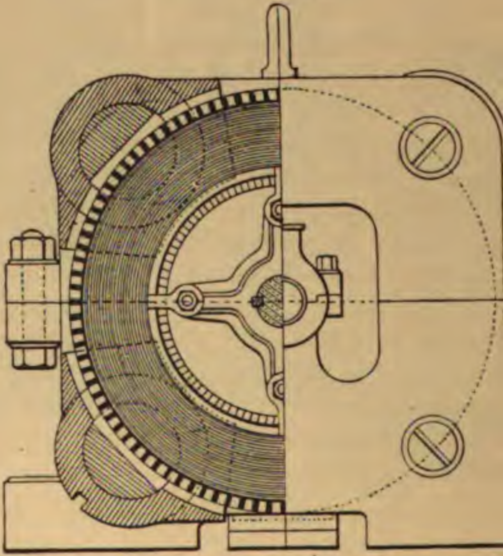
FIG. 336.



VICTORIA DYNAMO (showing Section and Method of Mounting the Ring).

external periphery of the armature core, there is
lation. The winding is of one continuous w
crossings are effected at the outer periphery.
prevented by the use at one end of a deeply-gro

FIG. 337.



VICTORIA DYNAMO (End View and Transverse Se

metal, thrust-bearing. Formerly, in a 4-pole
brushes were necessary—as in the Gülcher dy
4-pole Gramme. Mr. Mordey, as mentioned a
the number to two, by the device of cross-conn
brushes only are then necessary, and these are

The Victoria dynamo is usually compound-
all the eight magnet-cores wound with mai
inside and shunt coils outside, the main-circu
wound on slightly in excess of the amount need
an exactly equal potential at all loads. In a "
wound for a potential of 60 volts, the fol
were obtained:—Open circuit, 58 volts; 10
volts; 20 amperes, 59 volts; 60 amperes, 5

amperes, 59·9 volts; 120 amperes, 60 volts. It will be seen that for small loads the potential drops a little; but it is under these circumstances that the engine speed usually rises slightly in practice, so that the constancy of the potential between the mains is somewhat better than the figures would show. In actual practice the regulation is perfect, because the over-compounding serves to compensate for the drop of volts in the mains. The author has opened the circuit of a Victoria dynamo which at the time was feeding 101 lamps, 100 being at a distance, one lamp attached to the terminals of the machine. On detaching the main wire from the terminal, the 100 lamps were suddenly extinguished. The solitary lamp on the machine did not even wink, and there was no flash at the brushes. The sparking was so slight it was impossible to tell whether the machine was an open circuit or whether it was doing full work. The lead was the same under all loads. The machine depicted in Fig. 335 weighs 1904 lbs., and has an output of 18,000 watts at 1000 revolutions per minute. Such machines are now guaranteed under tender to run at a commercial efficiency of 92 per cent.

A larger type of Victoria machine, having six poles alternately N. and S. set round the ring, has also been constructed by the Brush Company. As each segment of the collector is connected with those situated at 120° and 240° distance round the set, only two brushes are required. A figure of this machine was given in the previous edition of this work.

The advantage originally claimed for the flat-ring construction, that it allows less of the total length of wire to remain "idle" on the inner side of the ring, is rather imaginary than real, for the total resistance of the armature is but a small fraction of the whole resistance of the circuit; and it is possible to spread the field so as to make all parts of the wire active without any gain whatever, if by this spreading there is no increase on the whole in the total number of lines of force in the field. The real reasons in favour of multipolar flat-ring armatures appear to be the following:—First, their excellent ventilation; second, their freedom from liability to be injured by the flying out of the coils at high speeds; third, their low resistance, due to the fact that the separate sections are cross-connected, either at the brushes, or in the ring itself, in parallel. To these points may be added that, with an equal peripheral speed, the armature rotating between four poles undergoes twice as much induction as when rotating between two poles, since it cuts the lines of force twice as many times in the former case as in the latter.

GÜLCHER CO.'S DYNAMO.

In this machine as originally brought out, the ring core consisted of a number of flat washers of sheet-iron clamped together, rotating in a 4-pole field, and furnished with four collecting brushes at the commutator. There were four hollow, box-like pole-pieces of iron, cast upon wrought-iron cores, embracing a considerable angular breadth. In recent years this machine has been greatly improved by the engineers of the Gülcher Electric Lighting Company. They have followed the same line of progress as that pursued in the design of the Victoria dynamo. The lamination of the cores has been tangential instead of radial; the field-magnets have been made more powerful; the pole-pieces have been reduced in breadth; and the number of the brushes has been reduced by cross-connexions in the armature to two. Fig. 338 shows an 8-pole type of machine, which has been largely used by this company both for lighting and for electro-deposition. In this cut the armature is covered from sight by guards of perforated metal. These machines have been made in all sizes up to 32 units.

The latest type of Gülcher dynamo is depicted in Figs. 339 and 340. In Fig. 339 the lower half shows a section in the vertical plane along the line A B, whilst the upper half represents a section in the oblique plane of the line A C, so as to show the true section of the polar portions. The drawings relate to a 4-pole 10-unit machine, designed to give 185 amperes, at 65 volts, at a speed of 900 revolutions per minute. The dimensions and details of construction are as follows: The end-yoke frames and the pole-shoes are of cast iron. The magnet-cores, 4 inches in diameter and 5 inches long, are screwed into the pole-shoes, and their other ends are turned down and fitted with circular nuts so as to secure a large contact-surface with the yokes. The armature is built up of rectangular charcoal iron wire wound upon a gun-metal pulley, forming a core of nearly square section. This is overwound with insulated copper wire in 80 sections of four turns

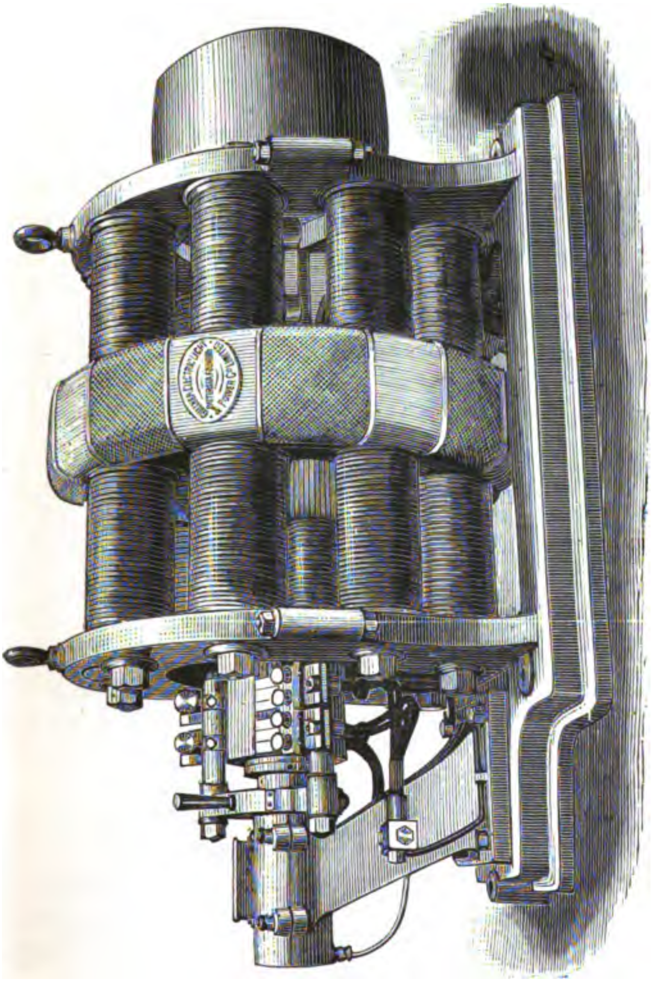


FIG. 338.

GÜLCHER DYNAMO.

each, the wire being rectangular, ·12 × ·85 i
single layer outside and in two layers inside

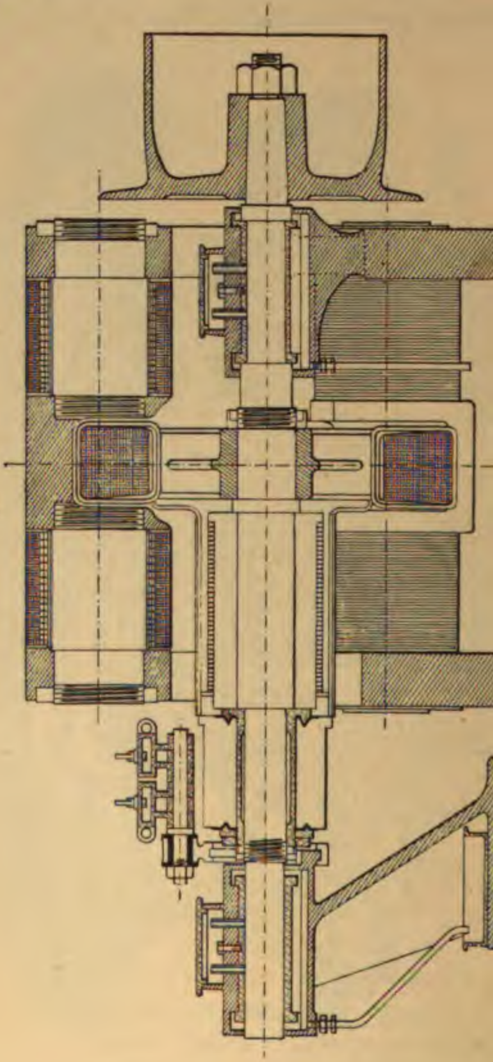
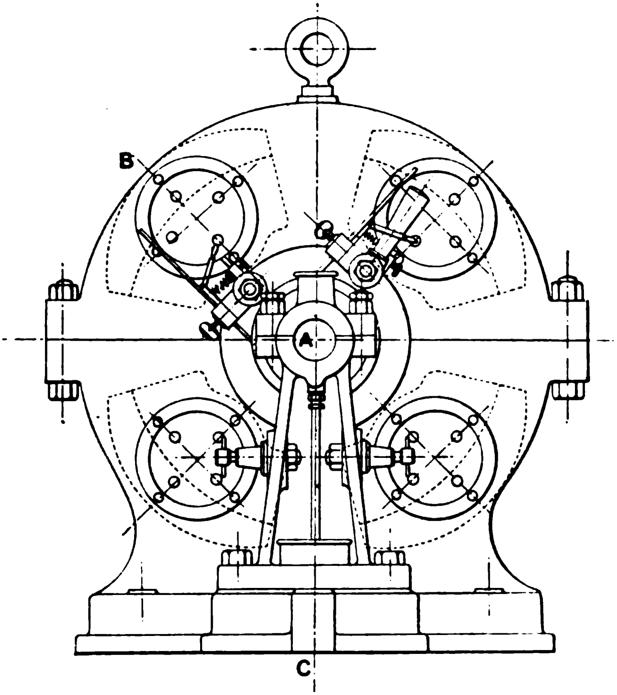


FIG. 339.

when finished has a square 3-inch section and
diameter. The resistance is ·025 ohm, and

copper is 18½ lbs. The commutator has 80 segments of hard-drawn copper insulated with mica ·75 mm. thick, clamped together, with proper insulation, over a gun-metal sleeve. The requisite cross-connexions between the opposite bars of the commutator are effected by a series of insulated copper rings, supported on a wooden sleeve placed between the armature and the commutator. Each ring has two lugs at opposite sides, these lugs being soldered to the wires that run from the ring windings to oppositely situated bars of the commutator. This machine is compound-wound, the windings being as follows :—Shunt coils of wire ·075 inch diameter, 8 layers of 44 turns each in each coil ; total weight of the 8 shunt coils, 77 lbs. ; total resistance joined in series, 7·805 ohms. Series

FIG. 340.



GÜLCHER CO.'S DYNAMO (End View).

coils of rectangular wire, ·13 × ·26 inch, in 2 layers of 14 turns each on each core; total weight of 8 series coils, 38 lbs.; total joint resistance of series coils, ·005 ohm.

RANKIN KENNEDY'S DYNAMOS.

This inventor has given the name of *iron-clad* to those forms of dynamo in which the field-magnets enclose the exciting coils.[1] One of these forms of field-magnet, which is discussed on p. 200, has four poles, two of them being salient poles protruding directly through the exciting coils on either side of the armature, the other two poles being consequent poles formed at the middle-points of the upper and lower portions of the iron framework, which here are bored away to form polar surfaces. Another form[2] of Kennedy's, having one coil only, resembles Fig. 121.

SIEMENS' DYNAMOS.

These originated with Messrs. Siemens and Halske of Berlin, who have manufactured many different forms. In recent years there has been some divergence between the types followed in Berlin and those produced by the London firm of Siemens Bros. Until the last year or two the characteristic feature in all forms was the drum armature; but the largest machines are now made with rings. In some of the earlier patterns of Siemens' machines the cores of the drum were of wood, over-spun with iron wire circumferentially before receiving the longitudinal windings. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. In all the modern drums iron core-disks are now used. The various modes of winding are described in Chapter XIII.

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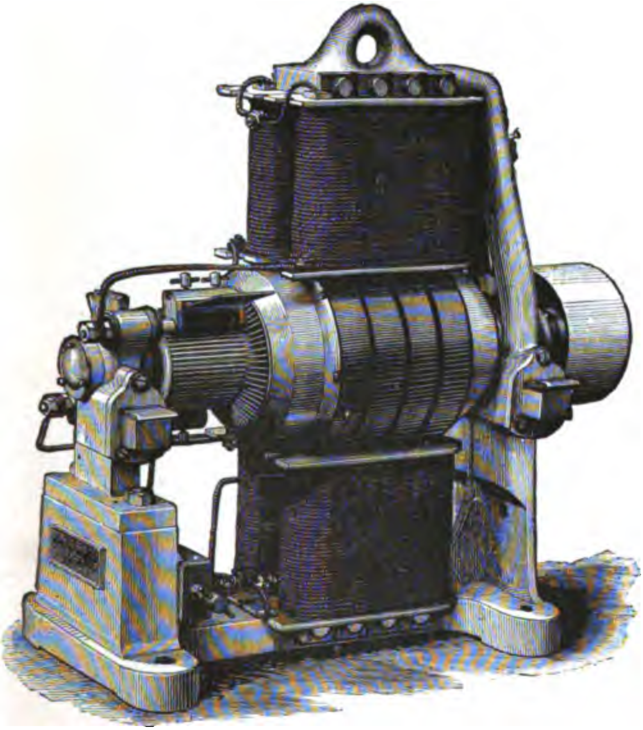
[1] An earlier type of "iron-clad" dynamo by the same inventor is described in *Industries*, i. 137, 1886.

[2] See data given by Jamieson in 1889 to Institution of Engineers and Shipbuilders in Scotland, printed in *The Electrician*, March 1, 1889.

pp. 361 to 364, and their theory on pp. 318 to 326. The old horizontal pattern of Siemens' dynamo is depicted in Fig. 8 p. 16. This was followed about 1880 by the vertical form shown in Fig. 341. The field-magnets here consist of forged arched bars of wrought iron, with double magnetic circuit, having consequent poles right and left of the armature. The coils are wound on flat brass frames slipped over the cores. In some of the machines provision is made for ventilation by leaving an air-space between the brass frames and the cores. About 1882 various ways of compound-winding were tried,[1]

FIG. 341.



SIEMENS' DYNAMO (Vertical Pattern).

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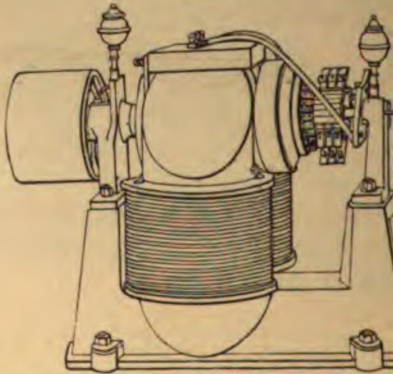
[1] See series of papers in the *Elektrotechnische Zeitschrift*, March—June, 1885, by Dr. O. Frölich.

in some of which the series and shunt-coils the same cores, and in others on different practice being to wind the series coils ou windings.

Some very large machines of the verti with many improvements in detail, includin compound-wound dynamos, "B 13" patter the Inventions Exhibition of 1885. Each of t of yielding 450 amperes at a potential of 2 an output of 112,500 watts, when running at per minute only. The armatures were woun copper.

In 1886 Messrs. Siemens and Halske, a intermediate forms (depicted on pp. 159 and 1 edition of this book), adopted the over-type 342. The field-magnet of this machine con very massive casting, over which the exciting

FIG. 342.

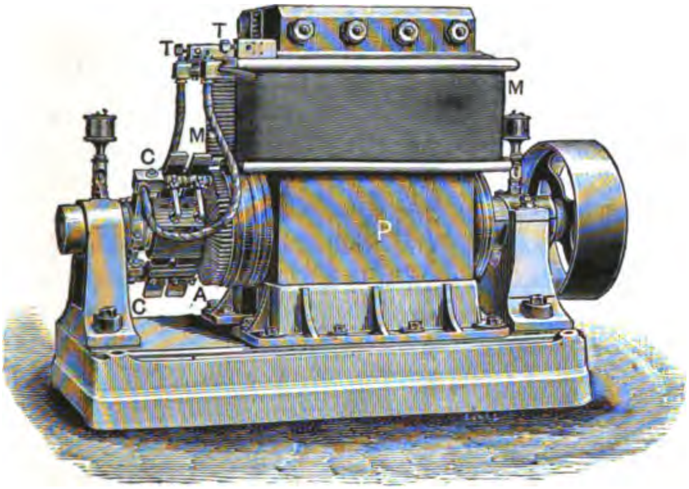


SIEMENS' DYNAMO (Berlin type of 188

The commutators of these machines are mas of iron bars attached by screws at one end o replaceable, and insulated by air-gaps. T adjustable; and they are trimmed with br so as to touch at least two collector-bars at c of brushholder used in all Siemens and Hal shown in Fig. 279, p. 385. Dynamos of this type are made for outputs from 1½ to 80 kilowatts, the largest having a peripheral speed of 14 meters per second.

The London firm has constructed much larger drum machines for central-station lighting, mainly of the under-type. Fig. 343 represents one of these machines, compound-wound, with the series winding on one limb only. At the Naval Exhibition of 1891 were shown three fine dynamos of 180 kilowatts each, at the slow speed of 350 revolutions per minute. The armature is 24 inches in diameter, 36 inches long, and weighs 2·4 tons; and the entire dynamo weighs 13·6 tons. The armature conductors are stranded bars; the commutator of hard-drawn copper, insulated with mica, with 144 segments, 9 inches long, with three pairs of brushes to collect the 1500 amperes. The rocker is provided with worm-wheel to adjust the proper lead. There are two independent circuits of 72 turns each, which are put in parallel with one another by the brushes, which are made broad enough to overlap three consecutive bars of the commutator.

FIG. 343.



SIEMENS' DYNAMO (London type of 1890).

Towards the end of 1886 a form of
machine, with ring external to the field-magn
out almost simultaneously by Messrs. Ganz
Messrs. Fein of Stuttgart, and by Messrs
Halske of Berlin.[1] It will be sufficient
machines of the latter firm.

The field-magnet, as shown in Figs. 344, 3
and internal to the ring. In the small machin
of a substantial cross-shaped mass of cast ir
centre of which passes the driving-shaft.
after receiving the exciting coils, are furnishe
pansions, which approach close to the inside o
ring itself is made up of thin iron washers
and supported on one side by a brass spide
shaft. A machine of this type, weighing 26
output of 25,000 watts at 480 revolutions p
a ring 20 cm. broad and of 64 cm. int
The advantages of this type are the ease
immense cooling surface of the armature, and
sity of applying binding-wires. In the first of
the commutator was hollow and consisted of st
with air insulation. In the larger machines the
commutator, the brushes being applied agai
of the ring itself.

Large ring machines of this type have b
the principal central stations[2] in Berlin and
Germany. In Plate XI. are given drawings o
machines, the largest hitherto made, from
Spandauerstrasse, Berlin, the scale being 1 : 80.
are mounted in pairs on the ends of the m
enormous compound condensing-engine of n
Kerchove and Co., of Ghent, having 5 feet 5 in
diameters of the cylinders being respectively

---

[1] For further information about the various machines of
technische Zeitschrift for April and May, 1887 ; *La Lumière*
1887 ; *Centralblatt für Elektrotechnik*, ix. 186, 410, and 581,

[2] See *Die Berliner Elektricitäts-Werke*, by Arthur Wilk
articles in *Elektrotechnische Zeitschrift*, x. 479, 563, 1889 ; xi.
Électrique, xxxvi. 441, 1890 ; and *Electrical World*, xvii. 14,

and 4 feet 5 inches, giving 1180 indicated HP., or 1000 actual HP., at 75 revolutions per minute. Each dynamo is capable

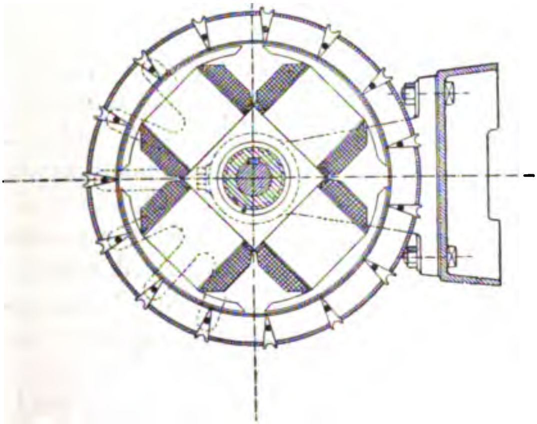


FIG. 344.

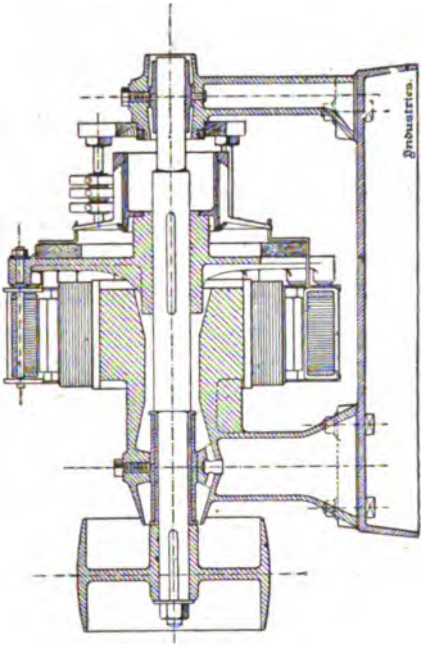


FIG. 345.

SIEMENS AND HALSKE'S RING DYNAMO (INTERNAL-POLE MACHINE).

of giving 2000 amperes at 140 volts, at only 60 revolutions per minute. The field-magnet has 10 salient poles, with

rectangular cores fixed to an annular yok
carried in a U-shaped support on the bearing.
section on the right-hand end of Fig. 1, P
exciting coils are all joined together in series,
in shunt to the armature. The armature is bu
mounted on insulated arms, which project fror
wheel, thus overhanging the field-magnet.
shows the detail of construction. The windin
shows, consists exteriorly of straight copper
other pieces of bent form which pass through
ring from the end of one straight bar to the b
next, thus constituting a spiral and endless
collecting brushes trail against the exterior
in the perspective view, Plate XI., Fig. 3.
diameter of the armature, which thus serves
is 9 feet. The brush-holders *e* in Fig. 1,
mounted on a stellate rocker *g*, by which
simultaneously shifted forward or back by t
shown in Fig. 3, Plate XI. The brushes
raised simultaneously out of contact by a le
connecting rods to another star-piece. Their
that shown in Fig. 279, p. 385. At the S
station are four such engines of 1000 non
driving two dynamos, supplying in total 4
lamps. At the Markgrafenstrasse station are
dynamos of 400 HP. each. At the Mauerst
three double steam dynamos of 1000 HP., a
400 HP. each. At the new Schiffbaudamm
double steam dynamos of 1000 HP. each.

At the Frankfort Exhibition of 1891 a
was shown[1] direct-driven from a triple conde
Kuhn of Stuttgart, of 300 kilowatt capaci
amperes at 150 volts at 65 revolutions p
magnet of this dynamo had 10 poles, being
meter. The external diameter of the ring wa
with 810 convolutions, each bar being about
paper insulation. There were 10 sets of b

---

[1] See description by Esson in *Electrical Review*, xxi

each set, each brush being 4·5 cm. wide, of rectangular copper wire. The star-piece carrying the overhung armature was of cast iron, with 30 arms, supporting the core-disks by means of 30 insulated steel bolts. To collect the currents the five positive brush-sets are united together, and the five negatives are also connected together; the currents being conveyed to the mains by flexible cables. At a speed of 100 revolutions per minute this machine reaches an output of 600 kilowatts.

EDISON DYNAMOS.

In 1879, after proposing a strange sort of machine as generator, in which inductive coils were waved to and fro at the end of the prongs of a gigantic tuning-fork, Mr. Edison, with the assistance of Mr. Upton, designed the machine which is depicted in Fig. 346. It has a drum armature rotating between heavy pole-pieces excited by a very long magnet with tall columnar limbs. The "Z" pattern of machine was capable of lighting 30 Edison lamps. In the Edison armatures the number of sections of the winding is an odd number.

In the first machines there were seven paths, as shown in Fig. 208 (p. 319), taken from Edison's British Patent Specification. In his large "steam dynamo" of 1881 the number of sections was 49. One consequence of this peculiarity of structure is, that if the brushes are set diametrically opposite to one another, one will touch the middle of a bar of the collector at the instant when the other slides from bar to bar. In Edison's larger dynamos the armature is made of bars of copper. The mode of connecting the ends by means of copper washers is described on p. 365. For larger machines two or three tall field-magnets like Fig. 346 were assembled side by side, over an armature of double or triple length. An Edison 60-light "Z" machine of the older pattern, tested by the Committee of the Munich Exhibition, was found to give an efficiency, which, if measured by the ratio of external electric work to total electric work, exceeded 87 per cent.; but its commercial efficiency—the ratio of external electric rectangular cores fixed to an annular yok carried in a U-shaped support on the bearing. section on the right-hand end of Fig. 1, exciting coils are all joined together in series in shunt to the armature. The armature is b mounted on insulated arms, which project fro wheel, thus overhanging the field-magnet. shows the detail of construction. The windi shows, consists exteriorly of straight copper other pieces of bent form which pass through ring from the end of one straight bar to the next, thus constituting a spiral and endles collecting brushes trail against the exterior in the perspective view, Plate XI., Fig. 3 diameter of the armature, which thus serves is 9 feet. The brush-holders *e* in Fig. 1 mounted on a stellate rocker *g*, by which simultaneously shifted forward or back by shown in Fig. 3, Plate XI. The brushes raised simultaneously out of contact by a le connecting rods to another star-piece. Thei that shown in Fig. 279, p. 385. At the station are four such engines of 1000 no driving two dynamos, supplying in total lamps. At the Markgrafenstrasse station are dynamos of 400 HP. each. At the Mauers three double steam dynamos of 1000 HP., 400 HP. each. At the new Schiffbaudam double steam dynamos of 1000 HP. each.

At the Frankfort Exhibition of 1891 a was shown[1] direct-driven from a triple cond Kuhn of Stuttgart, of 300 kilowatt capa amperes at 150 volts at 65 revolutions p magnet of this dynamo had 10 poles, bein meter. The external diameter of the ring w with 810 convolutions, each bar being about paper insulation. There were 10 sets of each set, each brush being 4·5 cm. wide, of rectangular copper wire. The star-piece carrying the overhung armature was of cast iron, with 30 arms, supporting the core-disks by means of 30 insulated steel bolts. To collect the currents the five positive brush-sets are united together, and the five negatives are also connected together; the currents being conveyed to the mains by flexible cables. At a speed of 100 revolutions per minute this machine reaches an output of 600 kilowatts.

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[1] See description by Esson in *Electrical Review*, x

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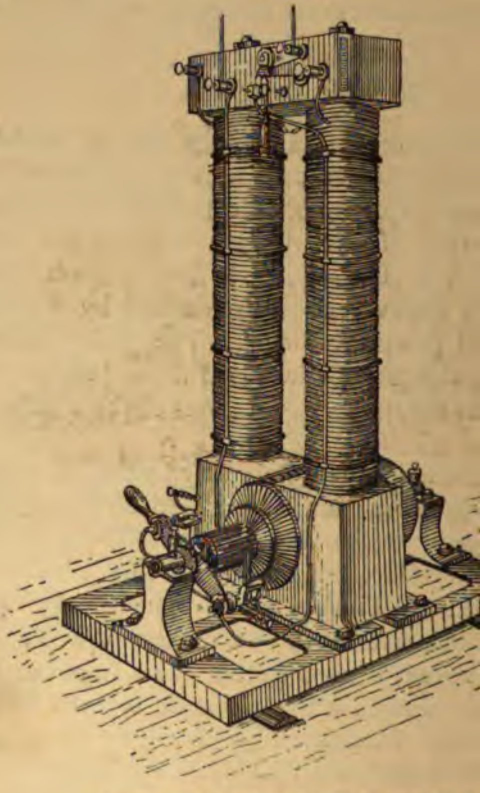
work to mechanical energy imparted at the
at the most, 58·7 per cent. This was due to
of wasteful eddy-currents in the bolts which h
armature and other masses of metal. The "
dynamos were even less efficient, and required

FIG. 346.



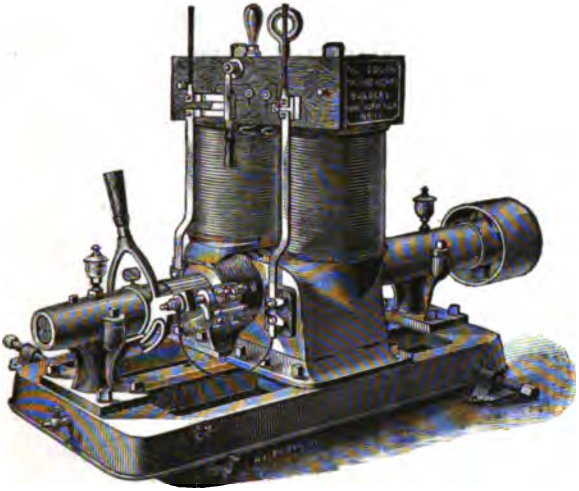
EDISON DYNAMO, "Z" PATTERN (188

be attached to the armature shaft to keep t
forced draught of air.

Dr. J. Hopkinson's efforts to improve this m
as detailed below, in a better design.

The field-magnets of all the larger machi by Edison prior to 1884 had a number of long iron columns as cores to receive the coils. Since that date the more compact arrangement of a single magnetic circuit with short stout magnets has been adopted by the Edison companies on both sides of the Atlantic. The usual form (type of 1888) of Edison dynamo, as used in the States, is depicted in Fig. 347.

FIG. 347.



EDISON DYNAMO (1888 Type).

The field-magnets are of cast iron, with a massive yoke, and stand upon a high footstep of zinc to diminish magnetic leakage through the bed-plate. These machines are shunt-wound, and are intended for incandescent lighting work. The bearings are longer and the mechanical arrangements in every way superior to those of the older machines.

At the Paris Exhibition of 1889 were a number of dynamos built by the Edison Machine Company, of Schenectady, ranging from a small 2½ kilowatt machine, 15 inches high, to one of 150 kilowatts, 102 inches high. Figs. 1 to 4, Plate VII., depict two of these machines, Figs. 1 and 2 are drawings of the largest machine. This dynamo is capable of supplying 1250 amperes at 140 volts, when running at 250 revolutions per minute. It has a 41-part commutator and an 82-bar armature. There are six brushes in each set, each 1·88 inches wide and about 0·62 inches thick. Its weight is 12½ tons.

Some particulars published in 1890 by M. Minet[1] concerning some of these dynamos show that the speeds vary from 2000 revolutions per minute in the 2½ kilowatt machine up to 800 in a 45 kilowatt machine. The peripheral speeds varied from 12·5 to 14 metres per second. Mean value of B in gap space from 3200 to 4100. The gross efficiency of the larger machines was about 95·6 per cent.; the electrical efficiency 93·8; the net efficiency about 89·7 per cent.

Since returning from Europe in 1889 Mr. Edison has designed some larger multipolar dynamos direct-driven from vertical triple-expansion engines. Plate XIII.[2] shows two 100 kilowatt dynamos fixed at the ends of the crank-shaft, precisely as with the larger Berlin dynamos. The engine is of 300 HP. at 176 revolutions per minute. The field-magnets are external, with eight consequent poles; and the armature is ring-wound. The conductors are made up of straight pieces on one face of the ring joined by U-shaped pieces into a continuous winding. The straight pieces serve also as commutator against which the eight sets of brushes press. There are 944 convolutions; and as alternate sets of brushes are connected together, there are really eight rows of 116 turns each in parallel. Each dynamo gives 666 amperes at 150 volts. The armature resistance is 0·006 ohm; that of the field-coils 8·45 ohms.

A smaller size of machine of the same type is shown in Figs. 348, 349, each of the two dynamos being of 75 kilowatts capacity. The new central station in New York will be equipped with 14 such machines, each with two 400 kilowatt dynamos. It will therefore be like the European kind of central station, and quite unlike the usual American central station, in which the most conspicuous feature is leather, a large number of small dynamos being driven by belts from countershafts.

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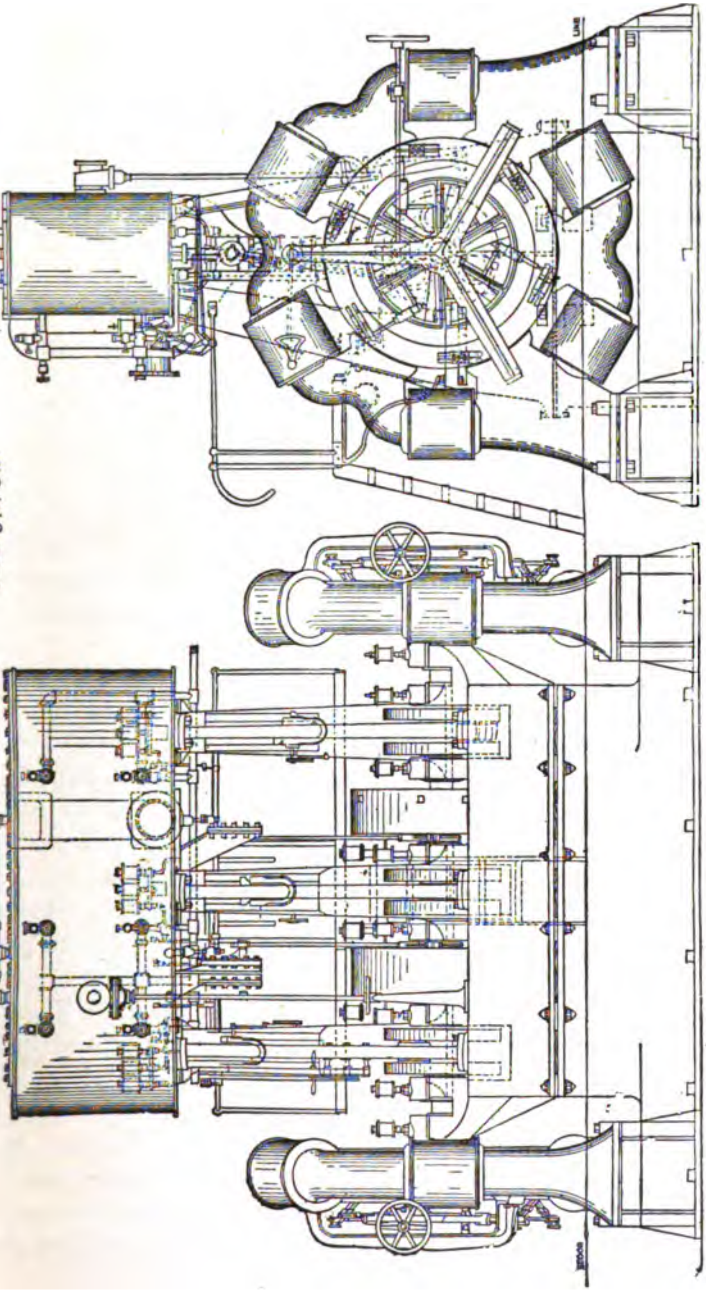
[1] *La Lumière Électrique*, xxxv. 401, 1890.

[2] See *Electrical Engineer* (N.Y.), xi. 489, 1891; by the courtesy of the editors of which journal the use of Plate XIII. is permitted.

FIGS. 348, 349.

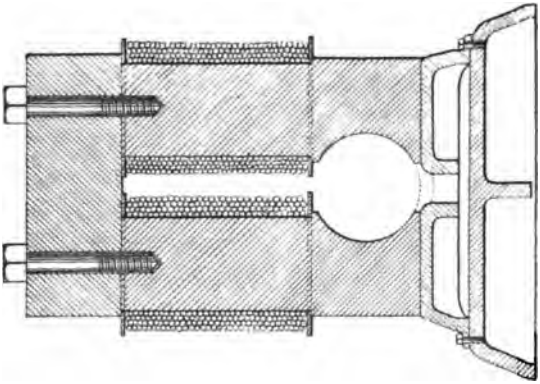


EDISON GENERAL ELECTRIC CO.'S MULTIPOLAR DYNAMOS.

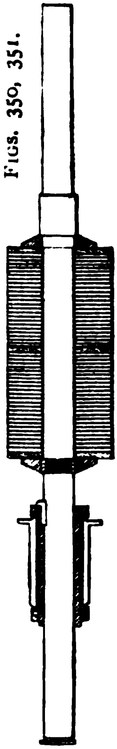
EDISON-HOPKINSON DYNAMOS.

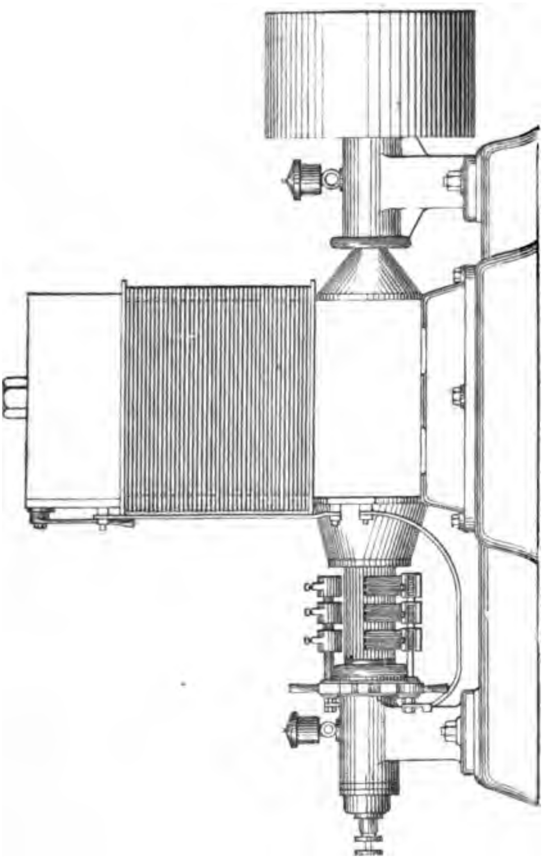
The Edison dynamo has received very mat
ments at the hands of Dr. John Hopkinson.
improvements relate to the field-magnet; other
ture. Dr. Hopkinson, in the first place, abolis
the multiple field-magnets, which in Edison's
"K," and "E" machines were united to comm
and instead of using two, three, or more round
each separately wound, he puts an equal mass
single solid piece of much greater area of cro
somewhat shorter length. One such iron mass,
in cross-section, is attached solidly to each pole
two are united at the top by a still heavier yok
machines have, consequently, a more squat an
pearance than before (Figs. 351 and 352).
also introduced the improvement of winding th
a copper wire of square section, wrapped in
This wire packs more closely round the iron
ordinary round wire. In the armature the fo
has been made:— The iron core in the older E
was made of thin iron disks, separated by pa
over a sleeve of *lignum vitæ*, and held togethe
tudinal bolts passing through holes in the c
secured by nuts to end-plates. These bolts ar
and the iron plates are held together by grea
ning upon screws cut on the axle of the armat
of the central hole in the plates has been di
getting into the interior more iron, and provi
cross-section for the magnetic induction. By
ments, a machine occupying the same ground
about the same weight as one of the older
machines, was made capable of supplying
economic coefficient being at the same time
new 250-light machine, the diameter of the
inches; its resistance (cold) is 0·02 ohm; that
is 17 ohms. The magnetization curve of the

FIG. 352.



FIGS. 350, 351.





EDISON HOPKINSON-DYNAMO: ELEVATION, SECTION, AND SECTION OF ARMATURE.

that even when doing full duty, the field-magnets are far from being saturated. It will be remarked that, in the older construction, the bolts and their attached end-plates furnished a circuit in which idle currents were constantly running wastefully round, with consequent heating and loss.

A remarkably complete account of one of these dynamos, constructed by Messrs. Mather and Platt, was published in 1886.[1] As this machine is often referred to in the theoretical chapters of this book, a detailed account of it is important. Its design may be gathered from Figs, 350, 351, and 352.

The machine described is intended for a normal output of 320 amperes at a pressure of 105 volts, running at 750 revolutions per minute. The field-magnet consists of two limbs connected by a yoke of rectangular section. Each limb, together with its pole-piece, is formed of a single forging. The wrought iron used for these and the yoke is of annealed hammered scrap; the magnetic properties being those described in Chapter VI. The section of the limbs is nearly rectangular, with rounded corners. The yoke is bolted to the limbs, the joints being well surfaced. The bed-plate is of iron, a zinc base 12·7 cm. high being interposed. The armature core is built up of about 1000 thin plates of soft wrought iron, insulated from the shaft, and separated by paper from one another. They are held between two end-plates, one of which is secured by a washer shrunk on the shaft, and the other by a screw-nut and lock-nut.

The following are the dimensions of the iron parts:—Diameter of armature core, 25·4 cm.; of internal hole, 7·62 cm.; of shaft, 6·98 cm.; length of core, 50·8 cm. Length of field-magnet limb, 45·7 cm.; breadth, 22·1 cm.; width (parallel to shaft), 44·45 cm. Length of yoke, 61·6 cm.; width, 48·3 cm.; depth, 23·2 cm. Diameter of bore of field-magnets, 27·5 cm.; depth of pole-piece, 25·4 cm.; width (parallel to shaft), 48·3 cm.; width between pole-pieces, 12·7 cm. Area of section of iron in armature core, 810 sq. cm. Angle subtended by bored face of pole-pieces, 129°. Actual area of pole-piece, 1513 sq. cm.; effective area, 1600 sq. cm. Thickness of gap space, 1·5 cm. Area of section of limbs, 980 sq. cm.; ditto of yoke, 1120 sq. cm.

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[1] See paper on *Dynamo-electric Machinery*, by Drs. J. and E. Hopkinson, in the *Philosophical Transactions* for 1886, Part I. This most valuable paper was reprinted, but without the plates, in the *Electrical Review*, xviii. 1886. It was also printed in the *Electrician*, xviii. 39, 63, 86, and 175, in issues of Nov. 19th and 26th, and Dec. 3rd and 31st, 1886, where the figures of the plates are printed in the text.

The windings are as follows:—Magnetizing coils, 11 layers on each limb of copper wire, 2·413 mm. diameter. Total convolutions, 3260; total length, 4570 metres. Armature, 40 convolutions in two layers of 20 convolutions of stranded copper wire, consisting of 16 strands of wire 1·753 mm. diameter. Resistance (at 13·5° C.): field-magnet, 16·93 ohms; armature, 0·009947 ohm. Normal magnetizing current, 6 amperes. Commutator, 40 copper bars insulated with mica.

Recent tests with Edison-Hopkinson dynamos constructed by Messrs. Mather and Platt, of Manchester, show that they have an economic coefficient of over 95 per cent., and an actual commercial efficiency of over 93 per cent. These machines have usually from two to five separate brushes at either side, capable of separate removal, so that they may be trimmed without stopping the machine. In order to bring the neutral points of the commutator to convenient positions right and left, the connecting pieces which join the commutator bars to the armature windings are carried spirally through about 90°. The makers of these machines have modified in detail the winding of the armatures,[1] enabling them to use copper bars instead of stranded wire. They shape the pole-pieces to diminish distortion of field, and connect the armature bars across the ends of the armature by spiral connectors in two layers, like those used in Siemens' electroplating dynamos.

Figs. 353 and 354 depict the large 225 kilowatt dynamos built by Messrs. Mather and Platt for the South London Electric Railway. They are further shown in Plate XX. They have a maximum output of 450 amperes at 500 volts when running at 500 revolutions per minute. The limbs and yoke are of wrought iron, the polar masses of cast iron. The armature conductors are copper bars, and the resistance from brush to brush is 0·017 ohm. That of the shunt coil is 96 ohms, of the series coil 0·015 ohm. The compound winding is not, however, of much service for such rapidly varying loads as occur in railway work, for with such massive magnets

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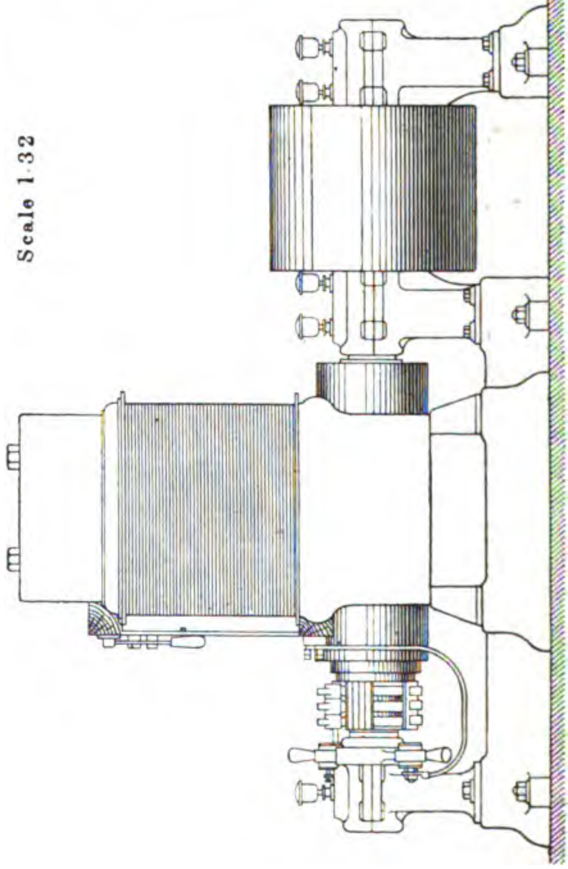
[1] See *Industries*, ii. 549, 1887; and Specification of Patent, 4884 of 1886.

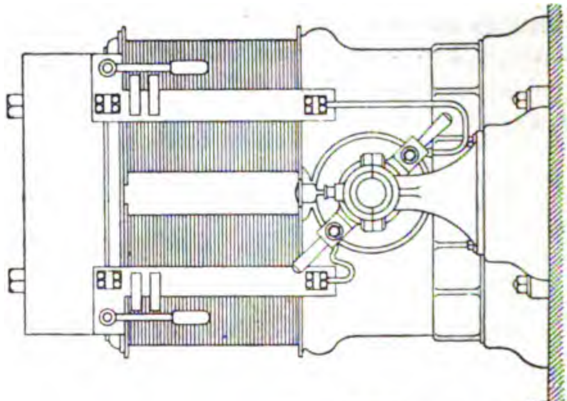
FIG. 353.



400 HP.

Scale 1:32

FIG. 354.



EDISON-HOPKINSON GENERATORS AT CITY AND SOUTH LONDON ELECTRIC RAILWAY.

changes of magnetism cannot take place rapidly enough. The weight of magnets and pole-pieces is 8·5 tons, that of the yoke 3·05 tons, of the armature 2·85 tons; whilst each complete machine with its bed-plate weighs 17 tons.

Some efficiency tests of a 53 kilowatt compound-wound Edison-Hopkinson dynamo direct-driven at 430 revolutions per minute by a Willans' engine have been published.[1] Indicated horse-power absorbed 85·3; output 475 amperes at 110 volts, or 52·2 kilowatts, or 70·0 horse-power; making a net efficiency of 83·3 per cent. The electrical efficiency was actually 96 per cent., the electrical losses being only 3 per cent., whilst 10 per cent. was lost in friction in engine and dynamo.

SCHUCKERT'S DYNAMOS.

The armature of the original Schuckert machine was a flat ring, the core of which was built up of a number of thin iron disks. The winding was identical with that of a Gramme machine, and the field-magnets resembled, in general, those of the typical Gramme. The ring was almost entirely enclosed between wide pole-pieces, each of which covered nearly half the ring. The ordinary pattern of machine is shown in Fig. 355, which shows how the frame admits of removing the armature. In recent years Messrs. Schuckert and Co. (of Nürnberg) have brought out many modified types of machines, but all having the flat-ring armature. The cores are now made of iron tape insulated with paper, coiled upon a brass foundation ring. Only the small sizes are made with two poles, all above 12 kilowatts being multipolar. As is the case with most German dynamos, the field-magnets are of cast iron, the commutator bars are insulated with paper, and the wires secured to them by screws. At the Frankfort Exhibition of 1891 a large number of these machines were shown,[2] the finest of them being a large direct-driven multipolar of a certain capacity of 230 kilowatts, giving 1000 amperes at 230 watts, and taking 320 HP. at 160 revolutions per minute. This machine, Plate XII., stands about 8 feet above the ground, into which it sinks nearly 3 feet. The external diameter of the ring is 240 cm., wound with 1120 turns of braided stranded wire: the cross-section of iron in it being

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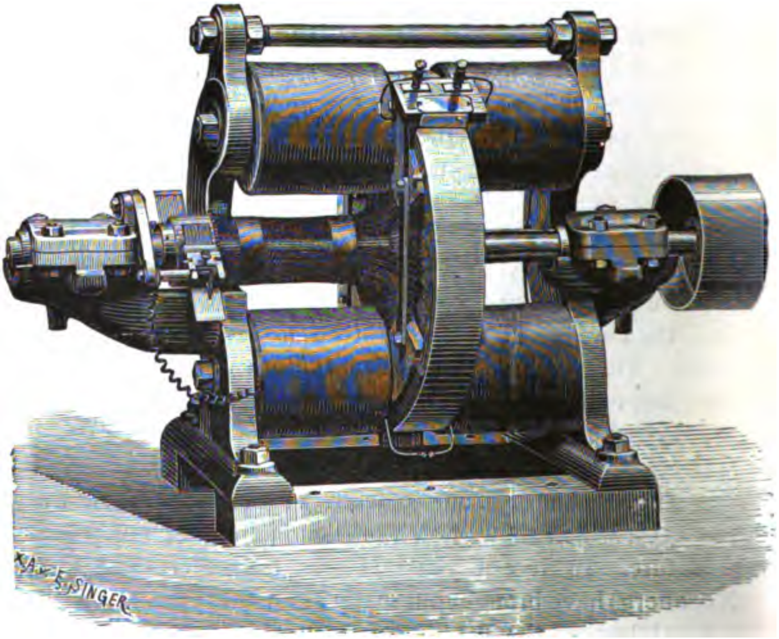
[1] *The Electrician*, xxv. 707, 1890.

[2] See article by Esson in *Electrical Review*, xxix. 526, 1891.

FIG. 355.



SCHUCKERT'S DYNAMO, WITH FLAT-RING ARMATURE.

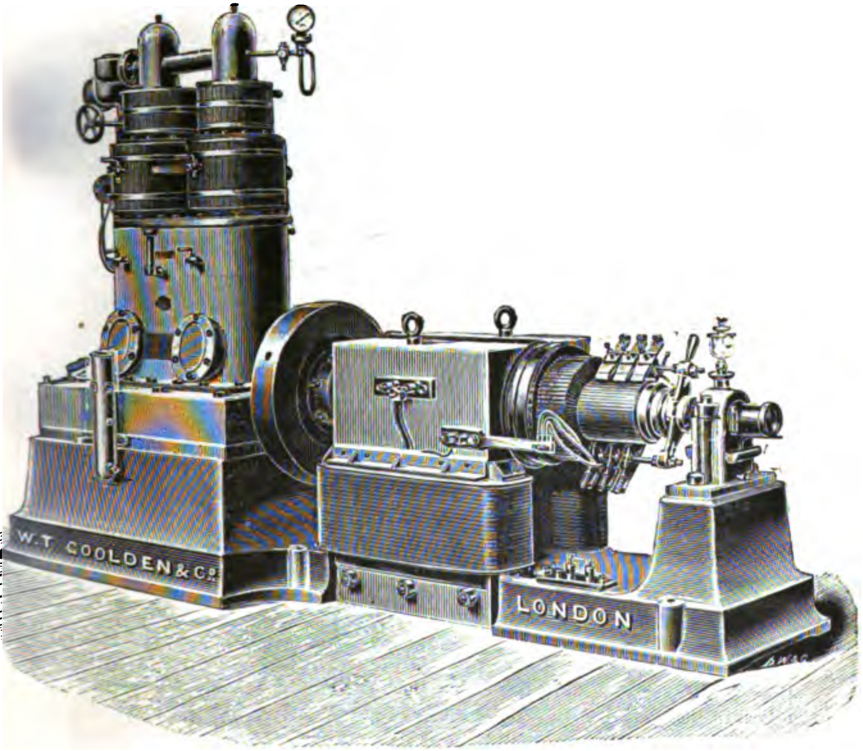
680 sq. cm. The commutator is 150 cm. in diameter, with 560 segments, cross-connected, so as to reduce the number of brushes. The resistance of the armature is 0·006 ohm; that of the magnet winding 7·4 ohms. There are 14 poles, and the armature winding is grouped in 14 rows of 80 turns each, all in parallel. The magnet poles project inwards from an external cast-iron case, divided horizontally. A thrust-bearing is provided to limit end-play, and this is carried on an outer bracket. There are four brush-holders, two positive and two negative, each carrying three brushes, each 5 cm. in

width, making a total width of 30 cm. for collecting 1000 amperes. A still larger machine with 16 poles is at work in the central station at Düsseldorf.

GOOLDEN'S DYNAMOS.

Excellent dynamos have long been manufactured by the firm of W. T. Goolden & Co. The calculation of their design by Mr. Ravenshaw has already been alluded to: their swivel bearings were noted on p. 394, their screw-fed brushes on p. 384, and their driving-horns of fibre on p. 355. In their larger dynamos bar armatures are employed, having rectan-

FIG. 356.



GOOLDEN DYNAMO AND WILLANS' ENGINE.

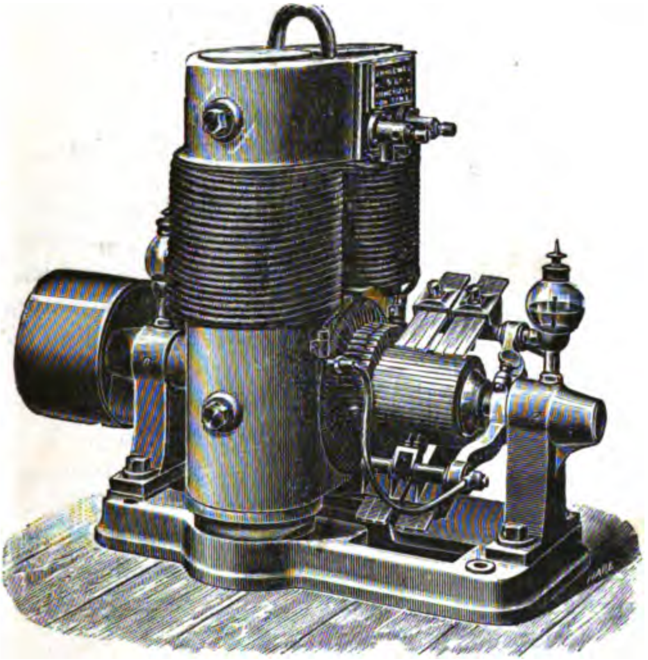
gular conductors built up of laminated or twisted copper strip, lightly oiled. The smaller are wound with round wire, silk covered. In Fig. 356 is illustrated a 61 kilowatt Goolden dynamo of the over-type, direct-driven at 460 revolutions per minute from a Willans' engine, so frequently used in central stations in England. The magnet limbs and pole-pieces are of wrought iron. The pole faces are bored elliptically, so as to leave greater air-space below armature than above, and counteract magnetic pull. The core-disks are of charcoal iron clamped upon a gun-metal spider. The conductor bars are driven by 80—100 fibre horns inserted in key-ways in the periphery of the core: they are united at ends by connectors made of spiral stamped plates of copper. At one end the bars are made fast to the segments of the commutator; at the other they are supported by an insulated brass ring, which allows them to expand longitudinally when they warm up. The commutator is of hard-drawn copper and mica, built up on a separate sleeve keyed to the shaft. The following tests were made of one of these combined plants, running at 500 revolutions per minute, showing the location of the various losses:—

	At Full Load.			At Half Load.		
Net output	..	50,000		..	25,000	
Loss in armature resistance	1,010			250		
Loss in magnet coils	615			590		
Loss by friction, eddy-currents, and hysteresis	255			255		
Total loss in dynamo	1,880	1,880		1,095	1,095	
Gross output	..	51,880	51,880	..	26,095	26,095
Loss in engine	..	..	5,920	..	..	5,920
Total indicated HP. in watts	..	..	57,800	..	..	32,015
Commercial efficiency of dynamo	96·2 per cent.			95·7 per cent.		
Commercial efficiency of combination	86·5 per cent.			71·8 per cent.		

HOLMES' DYNAMOS.

Messrs. J. H. Holmes & Co., of Newcastle-on Tyne, have introduced a compact and well-built form of Gramme machine, depicted in Fig. 357. It is known as the "Castle" dynamo; its yoke and pole-pieces are of cast iron, bored to receive the cylindrical upright wrought-iron cores. The ring armature core is made up of thin plates of charcoal iron. The commutator bars are forced together by hydraulic pressure before being clamped up. Messrs. Holmes have applied themselves very successfully to the problem of obtaining a constant output from a dynamo when driven at variable speeds.[1] The case in which this arises is in the lighting of

FIG. 357.



HOLMES' DYNAMO.

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[1] For various solutions of this problem see following Specifications of Patents: 342 of 1889 (Mordey); 3420 of 1889 (Sayers); and 20,244 of 1889 (Holmes). Also P. Hoho, in *Bull. de la Soc. Belge d'Électriciens*, March 1890.

railway trains by dynamos driven from the axles of one of the carriages. This they accomplished by a special combination of two dynamos, together with certain automatic switches. The larger dynamo is wound with two circuits upon the field-magnets, and its shaft is coupled to a smaller dynamo, the function of which is to send a demagnetizing current around the second circuit of the larger dynamo, so that as the speed rises its magnetism falls nearly in proportion. By this means the voltage is kept nearly constant, though the speed of the train may vary from 30 to 70 miles per hour.

LAURENCE, PARIS, AND SCOTT'S DYNAMOS.

In the modern machines by this firm the magnets are of the type Fig. 120, No. 8, with consequent poles, but more compact, and with deep nicks between the right and left-hand halves to diminish cross-magnetization. The armature conductors are bedded in deep narrow slots between iron teeth in the core-disks, which are threaded upon a hexagonal steel shaft. When compound-wound the series coils are usually wound first, and on the upper core-limbs only. For large machines the series coils are of sheet copper, insulated with strips of calico. The following data relate to a "C 6" dynamo wound for 120 amperes at 100 volts, at 710 revolutions per minute. The same machine with shunt winding only would serve for charging accumulators with 60 amperes at 130 volts, at 910 revolutions per minute.

There are 52 sections in the commutator, and two complete turns of conductor between each section. The sectional area of the iron in the armature core is 29·7. Sectional area of magnet cast iron 98 square inch. The magnetic density when giving 100 volts at 710 revolutions is nearly 138,000 lines per square inch. The armature conductor is of braided wire, and is extremely well insulated between inside and outside windings, and from the iron core.

Ampere turns in shunt 6468.

Ampere turns in series coils 3360.

The series winding consists of 28 turns of sheet copper 4½ inches wide, ·025 thick, on each of top magnets.

The current density in armature conductor is 3210 amperes per square inch, with 120 amperes.

Resistance of shunt coils 32·4 ohms watts lost with 100 volts ..	308
,, series coils 0·0124 ,, ,, ,, 120 amps. ..	178
,, armature coils 0·045 ohms watts lost with 120 amps.	648
Total watts lost	1,134
Watts in external circuit	12,000
Total watts	13,134

showing an electrical efficiency of 91·4 per cent.

“TYNE” DYNAMOS.

These machines, constructed by Messrs. Ernest Scott & Co., from the designs of Mr. Mountain, have mostly four consequent poles and a cross-connected armature. The arrangements of commutator, brush-holders, and rocker are of great excellence, and are depicted on Plate XV. The mode of holding together the commutator is designed to prevent creeping of oil into its interstices.

LAHMEYER'S DYNAMO.

This machine,[1] the magnets of which belong to the iron-clad type, is depicted in Fig. 358. It has been submitted to elaborate tests by Professor W. Kohlrausch. The machine, weighing 597 kilogrammes, gave 60 amperes at 65 volts, with a speed of 1250 revolutions per minute. The current density in the armature was 8·3 amperes per square millimetre of copper in section. The commercial efficiency was over 80 per cent. Though the field-magnets of cast iron were magnetized up to only 36 per cent. of their maximum, the armature current showed very little demagnetizing tendency. According to the inventor the waste magnetic field is less than 8 per cent. of the total field generated. The armature is wound on a plan suggested by Arnold of Riga, and independently suggested by Crompton, namely, the conductors are wound between teeth in the periphery of the core, after which the whole exterior of the armature is served with a thin layer of insulating material, and over this a layer of iron wires is wound. More recently Herr Lahmeyer has constructed in Frankfort[1] multipolar dynamos of kindred type.

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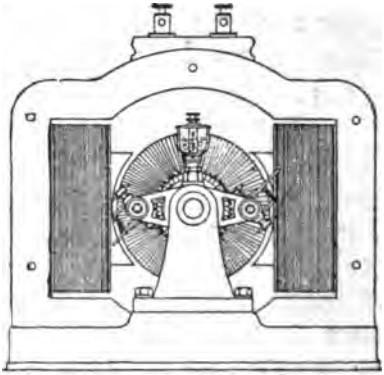
[1] See *Centralblatt für Elektrotechnik*, ix. 71 and 411, 1887; also *Elektrotechnische Zeitschrift*, ix. 89, 1888.

FIG. 358.



LAHMEYER'S DYNAMO.

"LEEDS" DYNAMO.

This machine (Fig. 359), made by Greenwood and Batley of Leeds, belongs to a type of machine with one exciting coil originated by the author (see Fig. 121, p. 200) in 1883. Similar designs have been used by Messrs. Goolden & Co., Messrs. Immisch, and Mr. R. Kennedy. The magnet-core is of soft wrought iron, the polar limbs—the lower one of which is in one piece with the bed-plate—are of annealed cast iron. The armature is ring-wound in a single layer, and is provided with a commutator of unusual length. The following are the dimensions of "Leeds" dynamos supplied to the Cadogan lighting station at Chelsea :—

35 kilowatt dynamo : Output, 70 amperes at 500 volts, 30 HP., at 800 revolutions per minute. Section of iron in armature core 84 sq. inches ; in magnets 87 sq. inches. Total length of magnetic

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[1] See *Electrical Review*, xxix. 404, 1891.

circuit 85 inches; ampere-turns on magnet 39,000. Air-gap, 345 sq. inches, by 0·57 inch from core to pole surface. $\mathsf{B}_{\prime\prime} = 86{,}400$. Diameter of armature (outside) 18·5 inches; length ditto, 14 inches; peripheral speed, 3900 feet per minute; weight of copper in armature, 115 lbs.; current density in armature, 3750 amperes per sq. inch; total turns in armature winding, 560; number of bars of commutator, 80.

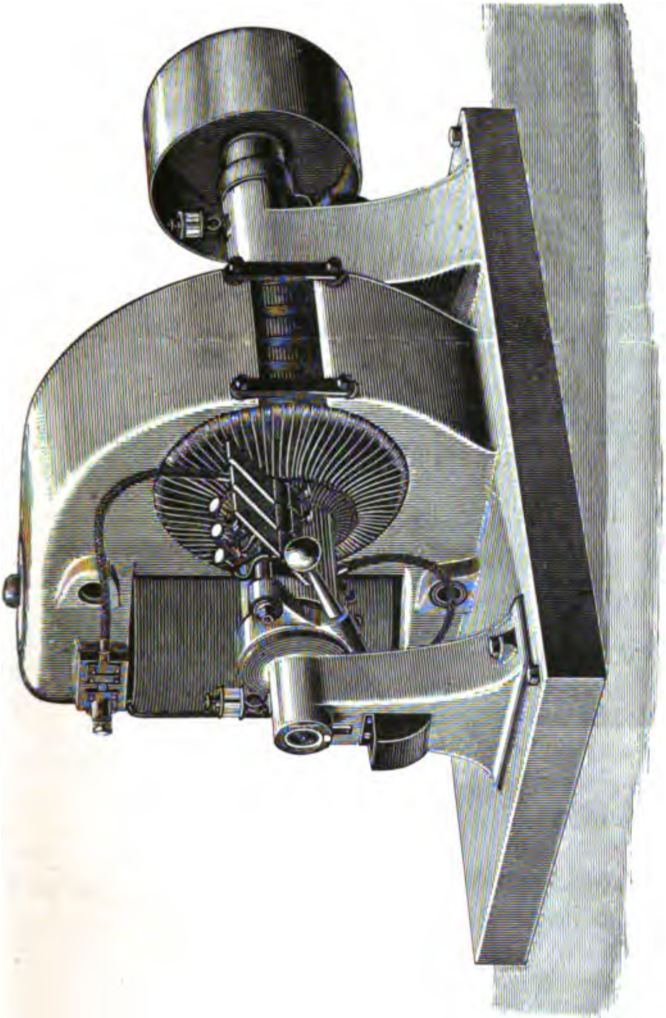


FIG. 359.

THE "LEEDS" DYNAMO.

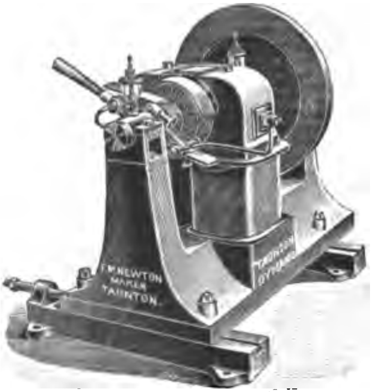
ELWELL-PARKER DYNAMOS.

Plate VI. depicts a 2-pole drum machine of 20 kilowatt capacity made by the Electric Construction Corporation, who have given the following particulars:—*Output:* 200 amperes at 100 volts; requiring 28½ HP. at 900 revolutions per minute. *Armature:* Core-disks 11¼ inches external diameter, 2¼ inches internal diameter. Number of conductors 104, each 0·05 square inch in section. Resistance 0·0154 ohm. Commutator has 52 segments, 6⅛ inches in length. *Field-magnet:* compound wound; resistance of shunt 28 ohms; of series winding 0·0021 ohm. The field-magnets of these machines are made up of several bars of wrought iron, with a thin cast-iron cap over the pole-pieces. The core-disks are threaded direct on the shaft. The chief insulating material used is a preparation of paper, impregnated with a special varnish. This firm has also constructed large 4-pole drum machines for central-station lighting.

"TAUNTON" DYNAMOS.

Messrs. Newton of Taunton produce excellent little machines, Fig. 360, of the same type as the preceding. One of these examined by the author ran absolutely sparklessly at all loads.

FIG. 360.



THE TAUNTON DYMANO.

GENERAL ELECTRIC TRACTION COMPANY'S DYNAMOS.

This firm has devoted itself to machines suitable for traction and mining purposes. The machine depicted in Fig. 361 was built from the designs of Mr. A. T. Snell. It has wrought-iron cores and cast-iron polar yoke pieces in the magnets. The brushes are of carbon; the holder is the same depicted in Fig. 277

(p. 382). This firm has also produced some large 4-pole dynamos of the same type as Fig. 1, Plate IX.

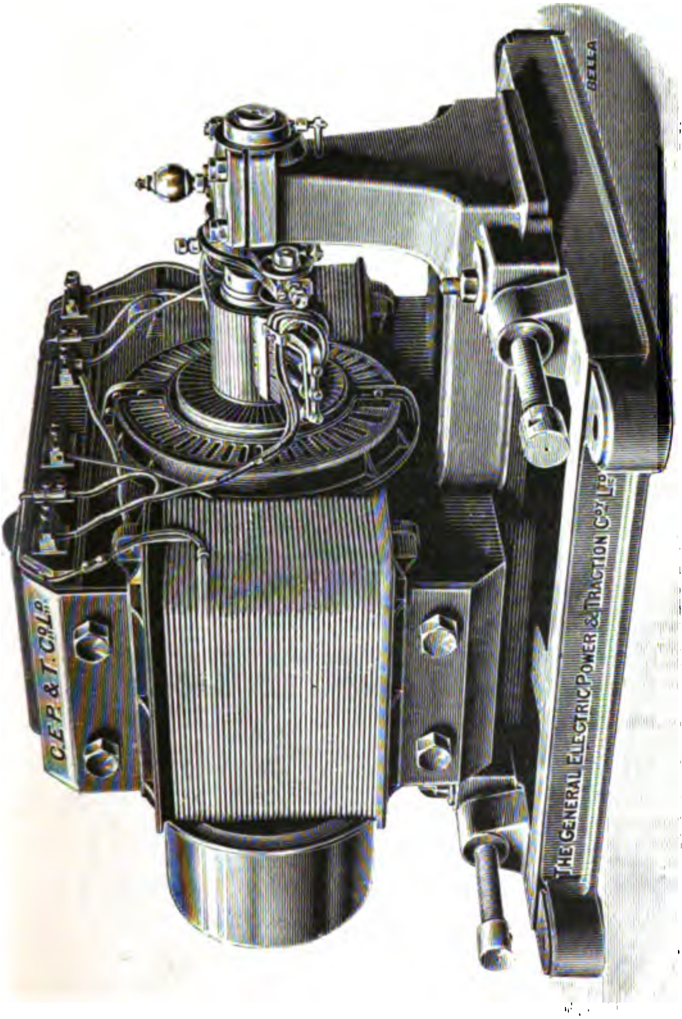

C.E.P. & T. Co. Ld.
THE GENERAL ELECTRIC POWER & TRACTION Co. Ld.

FIG. 361.

GENERAL ELECTRIC TRACTION COMPANY'S DYNAMO.

OTHER MULTIPOLAR DYNAMOS.

In recent years various other multipolar forms have appeared for central-station work. The Allgemeine Company of Berlin has constructed large 12-pole machines,[1] as well as 6-pole and 4-pole drum dynamos. The Thomson-Houston Company has designed a large 4-pole drum[2] closely

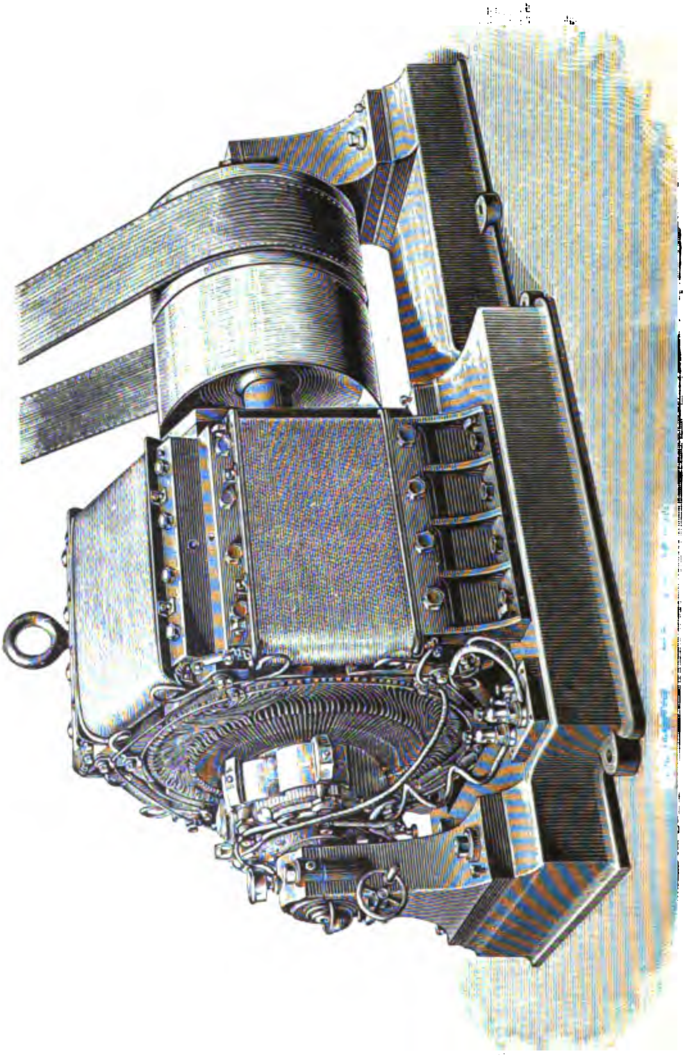


FIG. 362.

THURY'S DYNAMO

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[1] *Elektrotechnische Zeitschrift*, x. Sept. 1889.

[2] *Electrical World*, xiv. 335, 1889.

resembling Fig. 1, Plate IX. Large machines have also been turned out by Messrs. Latimer Clark, Muirhead & Co. of Westminster.[1] Messrs. Alioth & Co.[2] of Basel also construct multipolar drum dynamos. The Westinghouse Company is designing some large 6-pole machines.

THURY'S DYNAMO.

A 6-pole hollow-drum dynamo by Thury of Geneva is shown in Fig. 362. The method of the winding is described on p. 330, and the detail of the field-magnet on p. 201.

WENSTRÖM'S DYNAMO.

This form, which made its appearance in Sweden in 1882, has field-magnets of the iron-clad type, with two salient pole-pieces upon which the coils are borne, an external cylinder of iron, which encloses the machine, serving as the yoke. The armature has the peculiarity that the coils are wound in circular holes notched into the periphery of the armature core.

[1] *Electrical World*, xiii. 284, 1889.

[2] *La Lumière Électrique*, xxxii. 522, 1889.

CHAPTER XIX.

MISCELLANEOUS DYNAMOS.

IN this chapter are included Dynamos for Electrometallurgy, Unipolar Dynamos, Disk-Dynamos and other miscellaneous forms.

DYNAMOS FOR ELECTROPLATING AND ELECTRO-METALLURGY.

Special forms of dynamo are needed for the work of electroplating, electrotyping, and the electrolytic treatment of ores and purification of metals. They must, of course, be of the continuous-current type. In general, very low electromotive-forces and very large currents are requisite, for the quantity of metal deposited in the bath depends upon the quantity of amperes of current only, and not on the number of volts of electromotive-force. And though a few volts are necessary to drive the requisite current through the resistances of the circuit, the number is in every case small. To decompose water electrolytically requires less than two volts. To deposit metal in a bath in which the anode is of the same metal as the deposit requires usually a very small electromotive-force. In general, if too great an electromotive-force is employed, or if the density of current (i. e. the number of amperes per unit of area of kathode surface) is permitted, the metallic deposits will be uneven or pulverulent. All these circumstances point to the construction of dynamos having at most but four or five volts of electromotive-force, but so designed as to have an exceedingly low internal resistance.

The first application of a dynamo to the purpose of electroplating is due to Mr. J. S. Woolrich, who in 1842 patented this use of a magneto-electric machine. Wilde, however, was the first to construct machines really fitted for the purpose, when he invented the principle of using a large dynamo, the field-magnets of which were separately excited by the currents of a smaller magneto machine. His first machines, which were used for many years by Messrs. Elkington, had small exciters of the old Siemens type (Fig. 23), mounted upon electromagnets of the form shown in Fig. 119, No. 1. Both armatures were of the old shuttle-form introduced by Siemens, and the larger one required to be kept cool by streams of water. About the year 1867 Wilde introduced another type of machine, to which reference was made on p. 12. The armature coils (save the one used for feeding the field-magnets) are connected in parallel in the manner shown in Fig. 417. There are iron cores in the armature coils of this machine, which is, in consequence, prone to heat. Weston introduced a small machine for nickel-plating which had steel cores to the magnets but with main-circuit coils upon them, and an automatic cut-off to break the current, to prevent the magnetism from reversing by a back-current from the bath. Elmore introduced another machine with multipolar magnets and disk armature. The commutator merely rectified the currents (p. 40) without rendering them continuous. This is a bad feature: for with all electro-chemical work, whether plating, typing, or charging accumulators, there is necessarily much sparking, unless the fluctuations of the current are reduced to a minimum by employing a many-part armature with a proper collector. The largest Elmore dynamos, for copper refining, had eighteen electromagnets in each crown, and yielded a current of 3000 amperes at a potential of seven to eight volts. Such a machine would deposit over 25 lbs. of copper per hour. The field-magnet coils are in series with the main circuit. This is a mistake. All electroplating dynamos should be shunt-wound or they are liable to reverse. Gramme in 1873 built special forms of very low resistance with strip-wound armatures having a commutator at each end, and giving 1500 amperes at 8 volts. Siemens and Halske also were early in the field with machines having bar armatures, which they employed at their electrolytic works at Oker.[1] Brush also constructed machines of low resistance for electroplating purposes. It was for this type of machine that Brush made the important invention of exciting the field-magnets with a compound winding; coarse wire coils being connected in series, with the addition of a so-called "teazer" coil of finer wire—in other words, a shunt winding—to maintain the magnetism when the main circuit was opened, thus enabling the machine to do either a large or a small amount of work without fear of reversing the current. The potential at the terminals of this machine is fairly constant. It varied only from 3·3 to 4·1 volts, whilst the current varied from 300 amperes to zero.

Other dynamos have been designed for electroplating and electro-metallurgical work by nearly all the important manufacturers.

An Elwell-Parker depositing dynamo[2] gave 1500 amperes at 50 volts at 450 revolutions per minute; a 4-pole shunt-wound drum machine with 80 stranded conductors, each of 0·2 square inch section, on the drum, and a 40-part commutator. Armature is 20 inches long and 22 inches diameter, with an unusually long commutator. Four sets of brushes, five in each set. Length of active conductor 1600 inches. At peripheral speed of 2500 feet per minute generates 1 volt for each 8 inches of conductor.

A 50 kilowatt dynamo, by Paterson and Cooper,[3] for producing bleaching liquor electrolytically, gives 1200 amperes at 42 volts.

Another 50 kilowatt dynamo, designed by Hopkinson [4] for copper refining, gives 1000 amperes at 50 volts, at 400 revolutions per minute; resistance of armature 0·0016 ohm; commercial efficiency 93 per cent.; total weight 5¼ tons.

A plating dynamo by Stafford and Eaves[5] has solid and simple magnetic circuit with one exciting coil and a ring armature with only eighteen sections, giving 150 amperes at 6 volts at 640 revolutions per minute.

In dynamos for such purposes the requirement of large current and very low voltage introduces difficulties into the design, for the voltage cannot be obtained low enough without having either very few convolutions on the armature, or else a weak field-magnet, or else a very slow-speed machine. Slow-speed machines are always costly in proportion to their output. Machines with weak magnets give trouble with sparking. Machines with few massive conductors and few parts in commutator give trouble in sparking, and are liable to heat from local eddy-currents. A stranded conductor should be used, or several *independent* windings (see pp. 315 and 509), all put in parallel by brushes of special thickness.

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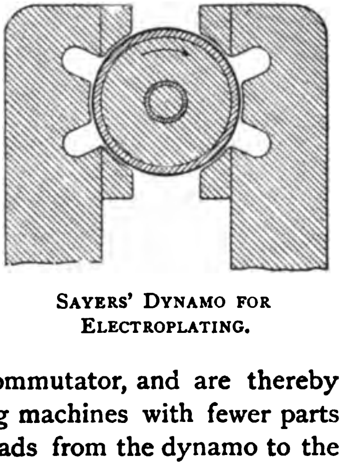
[1] See *Elektrotechnische Zeitschrift*, ii. 54.

[2] *The Electrician*, xxi. 183, 1888.

[3] *Ibid.*, p. 181. [4] *Ibid.*, xvii. 62, 1886. [5] *Ibid.*, xviii. 506, 1887.

Sayers has proposed an ingenious device to enable currents to be taken from a machine at various voltages. The pole surfaces are subdivided by deep nicks, as in Fig. 363, thus providing several neutral points on the commutator at which brushes may be placed without sparking. Thus, for example, whilst the potential between the two main brushes may be 10 volts, an intermediate brush may be employed to divide this into 7½ volts for nickeling and 2½ volts for silver-plating.

FIG. 363.



SAYERS' DYNAMO FOR ELECTROPLATING.

Messrs. Crompton & Co. have devised a method of dividing the main leads between two pairs of brushes touching adjacent bars of the commutator, and are thereby enabled to construct their plating machines with fewer parts in the armature. The divided leads from the dynamo to the plating tanks cost no more than a single undivided lead would do, but they interpose a comparatively large resistance in the path of the local current from the short-circuited section.

For the special purpose of the aluminium industry several types of machines have been developed. Messrs. Crompton & Co. built a very large 2-pole drum machine,[1] capable of

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[1] *The Electrician*, xxi. 590, 1888; also *La Lumière Électrique*, xxx. 207, 1888.

affording 5000 amperes at 60 volts. Mr. C. E. L. Brown[1] has made some 6-pole machines for 6000 amperes at 20 volts at 180 revolutions per minute. The armatures have each two separate windings with a commutator at each end, and at each commutator 36 brushes, arranged in six sets of six each. The field-magnet is like Fig. 131, but with six poles, and cast in one piece. The armature is 38 inches in diameter and 24 inches long. The windings were at first embedded in holes in the core-disks; but as troubles arose about insulation, the core-disks were turned down, and the armature re-wound with external conductors. Although there are as many brush-sets as poles, rendering cross-connexion of the windings not absolutely necessary, yet such cross-connexions are added to ensure equalization of the currents, equipotential segments of the commutator being internally cross-connected by rings with three projecting lugs. Mr. Brown has also made some 8-pole machines for an output of 14,000 amperes at 30 volts.

NUMERICAL STATISTICS ON ELECTRO-METALLURGY.

The following data are useful for reference in deciding what the electrical capacity of a dynamo must be in order that it may deposit metal in any desired quantity :—

Copper.

Current	1	ampere	deposits	0·000326	grammes	per second.
„	1	„	„	0·01957	„	per minute.
„	1	„	„	1·1739	„	per hour.
„	851·8	„	„	1	kilogramme	per hour.
„	386·4	„	„	1	pound	per hour.

To deposit 100 lbs. of copper in a working day of 10 hours will require 3864 amperes of current flowing all the time ; or, if conducted in ten baths in series with one another, will require 386·4 amperes, but in that case the dynamo will require to be of an electromotive-force ten times as great as for one single large bath. If electrolysis of the crude copper solution is carried on with carbon anodes, there will be required about 1·2 volts for each bath in series, or, at most, 15 volts for the ten baths.

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[1] *La Lumière Électrique*, xxx. 205, 1888.

Silver.

Current of 1 ampere deposits 4·025 grammes per hour.
„ „ 112·7 „ „ 1 pound per hour.

Gold.

Current of 1 ampere deposits 2·441 grammes per hour.
„ „ 185·8 „ „ 1 pound per hour.

Nickel.

Current of 1 ampere deposits 1·099 grammes per hour.
„ „ 412·8 „ „ 1 pound per hour.

The following statistics as to the various pressures and currents required in various processes of electro-deposition are useful for reference :—

PRESSURE AT TERMINALS REQUIRED FOR DIFFERENT KINDS OF BATHS.

	Volts.
Copper (acid bath)	0·5 to 1·5
„ (cyanide bath)	3 „ 5
Silver	0·5 „ 1
Gold	0·5 „ 4
Brass	3 „ 5
Iron (steel facing)	1 „ 1·3
Nickel on iron, steel, copper, with nickel anode, strike deposit with 5 volts, diminishing to	1·5 „ 2
Nickel on iron, steel, copper, with carbon anode	2 „ 4
Nickel on zinc	4 „ 7
Platinum	5 „ 6

CURRENT DENSITY FOR PROPER DEPOSIT.

Copper Typing—	Amperes per 100 sq. inch.
Best quality tough deposit	1·5 to 4
Good and tough (for clichés)	4 „ 10
Good solid deposit	10 „ 25
Solid deposit, sandy at edges	25 „ 40
Sandy and granular deposit	50 „ 100

	Amperes per 100 sq. inch.		
Copper (cyanide bath)	2	to	3
Zinc (for refining)	2	,,	3
Silver	1	,,	3
Gold	0·5	,,	1
Brass	3	,,	3·5
Iron (steel-facing)	0·5	,,	1·5
Nickel at first deposit 9 to 10 amperes per 100 square inches, diminishing afterwards to	1	,,	2

UNIPOLAR DYNAMOS.

Those dynamos in which rotation of a conductor effects a continuous increase in the number of lines of force cut, by the device of arranging one part of the conductor to slide on or round the magnet, are known[1] as *unipolar* machines.

The earliest machine which has any right to be called a dynamo (Fig. 1, p. 6), namely, the rotating copper disk of Faraday, was, in fact, of this class. So were his other machines with sliding connexions; for example, the copper cylinder rotating over the pole of a magnet (Fig. 3, p. 7). Plücker[2] devised another form, with a horizontally rotating magnet, having sliding contacts at the middle and at either end. In 1862 Mr. S. A. Varley had a unipolar apparatus with an iron magnet rotating in a vertical frame having a mercurial connexion at the middle-point. About 1878 Dr. Werner Siemens[3] designed a unipolar machine in which there were two cylinders of copper, both slit longitudinally to obviate eddy-currents, each of which rotated round one pole of a U-shaped electromagnet. A second electromagnet was placed between the rotating cylinders, with protruding pole-pieces of arching form which embraced the cylinders above and below.

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[1] This sounds like a *lucus a non lucendo*, for the magnet has two poles. But the name is derived from the term "unipolar induction," which continental electricians, following Prof. Wm. Weber, give to the induction of currents by the process of "continuous cutting," which we are now dealing with. I do not adopt the term, as it is needlessly mystifying.

[2] *Pogg. Ann.*, lxxxvii. 352, 1852.

[3] *Elektrotechnische Zeitschrift*, ii. 94, 1881.

Each cylinder, therefore, rotated between an internal and an external pole of opposite polarity, and consequently cut the lines of force continuously by sliding upon the internal pole. The currents from this machine were very great, but of only a few volts of electromotive-force. To keep down the resistance, many collecting brushes pressed on the cylinders at each end. This dynamo was used at Oker for depositing copper. Much attention has been paid in recent years to machines of this type, and the author himself designed one in which two Faraday disks, coupled at their peripheries outside an internal stationary pole-piece, rotate in a symmetrically uniform field. Mr. Willoughby Smith showed that if an iron disk be used instead of a copper disk a much more powerful effect is obtained. Prof. George Forbes has constructed several machines of this class. Originally he began by employing an iron disk which rotated between two cheeks of opposite polarity, the current being drawn from its periphery. He then doubled the parts. The next stage was to unite the two disks into one common cylinder, rotating within an entirely self-contained iron-clad field-magnet. For this reason the inventor prefers to call this type of dynamo "non-polar." A rubbing contact—for which purpose Prof. Forbes at one time used carbon brushes, and at another a number of springy strips of metal foil—is maintained at the two extremities of the periphery. One of the earlier forms of machine, with a single disk 18 inches in diameter, was stated to give 3117 amperes at a potential of 5·8 volts when running at 1500 revolutions per minute. One of the later machines, in which the armature is a cylinder of iron 9 inches in diameter, 8 inches long, is designed to give a current of 10,000 amperes at 1 volt, at 1000 revolutions per minute. The electromotive-force of such machines increases as the square of the diameter. Other types have been designed by E. Ferraris, E. L. Voice, Delafield, Hummel, and others. All the important forms prior to 1885 are described and discussed by Uppenborn in the *Centralblatt für Elektrotechnik* of that year, p. 324.

Two difficulties seem to beset this type of machine, namely, the inherent trouble of peripheral collection of large currents, and the very considerable armature reactions which accompany these large currents, causing great fall in the voltage[1] as the current increases. The latter can only be obviated by the same expedients as hold good in all other types of dynamo, namely, to make the field-magnets relatively powerful and to counterbalance the reactions by compounding or over-compounding the machine by the use of series windings.

The theory of the unipolar disk-dynamo has been given by Sir W. Thomson,[2] who has shown that such a machine is not self-exciting except above a certain critical speed, dependent on the resistance of the circuit. The latest suggestions came from Atkinson,[3] whose machine is self-exciting, and Mr. C. E. L. Brown has communicated to the author some results and drawings of a unipolar machine built at the Oerlikon Works, with a cylinder of copper rotating between the lips of an iron-clad electromagnet of cast iron. This machine at 1200 revolutions per minute worked at 10 volts and showed hardly any perceptible drop in voltage when 3000 amperes were taken from it.

DISK-DYNAMOS.

In the dynamos of this class the coils are carried round to different parts of a magnetic field, such that either the intensity differs in different regions, or more generally the lines of force run in opposite directions in different parts of the field. Fig. 17 (p. 29) illustrates this principle; and we shall now consider how it is carried out in practice. In the early machines of Saxton, Clarke, and Stöhrer, single pairs of coils were mounted so as to pass in this fashion through parts of the field where the magnetic induction was oppositely directed. Such a machine will, therefore, give alternate currents, unless a commutator be affixed to the rotating axis. Niaudet's obsolete dynamo, which may be regarded as a compound Saxton machine, having the separate armature coils united as those of Gramme and Siemens into one continuous circuit, was furnished with a radial collector instead of a cylindrical one. In the Wallace-Farmer dynamo was very nearly realized the condition of field of Fig. 17, there being a pair of poles at the top arranged so that the N. faces the S. pole, and another pair at the bottom where the S. faces the N. pole. In 1878 von Hefner Alteneck designed a disk-dynamo in which the number of coils differed by two, or some other number, from those of the field, and with the employment of a multiple bar commutator with complicated cross-connexions. In 1881 Hopkinson and Muirhead showed a disk-dynamo with a wave-winding. In 1875 Professor Pacinotti devised[1] a form of disk-armature, which he described as a "transversal electromagnetic fly-wheel." The machine, which was exhibited at Paris in 1881, had for field-magnet two electromagnets placed with their contrary poles juxtaposed, forming, as shown in Fig. 364, a single magnetic circuit with two gaps. Through these two gaps passed a disk-armature, constructed of radial conductors arranged to cut the intense magnetic fields. The electromotive-forces induced in these conductors would on the one side be directed radially inwards, on the other radially outwards. The method devised by Pacinotti for connecting the radial conductors into a single closed coil is shown in Fig. 233, p. 338. Another form was the obliquely-coiled dynamo of Ayrton and Perry of 1882. Another disk-armature was designed about the same time by Mr. Edison with radial bars, connected at the outer ends by concentric hoops and at the inner by copper washers. A more recent form of the same inventor is shown in Fig. 235, p. 340. Another type of disk-armature was invented by Sir W. Thomson, consisting of a

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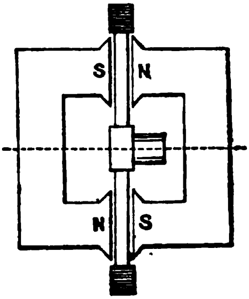
[1] See some figures given by Hummel in vol. ii. p. 19, of Kittler's *Handbuch der Elektrotechnik.*

[2] On a uniform electric current accumulator (*Phil. Mag.*, January 1868; and *Reprint of Papers*, p. 325).

[3] *La Lumière Électrique*, xxxv. 557, 1890.

FIG. 364.



FIELD-MAGNETS OF PACINOTTI'S DISK-DYNAMO.

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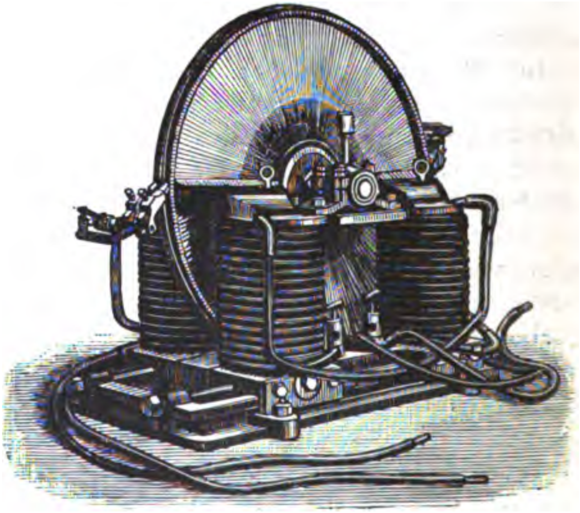
[1] *Nuovo Cimento* [3] x., September 1881.

wheel with spokes like a bicycle wheel, with collecting brushes pressing against opposite ends of a diameter. Bollman[1] devised a multipolar machine, having a complex armature built up of radial strips of copper connected in zigzag and joined to a cross-connected commutator. More recently machines of this class have been devised by Desroziers,[2] Robin,[3] Jehl and Rupp,[4] and Sayers.[5] In the machine of Jehl and Rupp, which is brought out by the French Edison Co., there are four pairs of opposing poles.

FIG. 365.



POLECHKO S DISK-DYNAMO.

With 24 kilogrammes of copper in the armature, and running at 735 revolutions per minute, this machine gives 350 amperes at 110 volts.

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[1] For detailed drawings and description, see *Centralblatt für Elektrotechnik*, ix. 7, 1887.

[2] See *La Lumière Électrique*, xxiv. 293, 294, and 517, 1887; xxix. 401, 1888.

[3] *Ibid.*, xxiv. 544, 1887.

[4] *Ibid.*, xxiv. 343, 1887. See also detailed illustrations and description in xxv. 368, 1887; and in *Electrician*, xix. 94, 1887.

[5] Specification of Patent, 717 of 1887.

Fritsche's Disk-Dynamos.—These dynamos[1] have a disk with multipolar wave-winding with series grouping for armature. The interesting constructional feature of these machines is the use of wrought-iron bars, instead of copper, as the active conductors in the disk. The commutator is fixed to the outside of the disk, with the brushes trailing against the periphery at two points.

Polechko's Dynamo.—This form[2] realizes Sir W. Thomson's suggestion for a wheel-dynamo. The wheel is 1 metre in diameter, with narrow copper spokes to rotate in a narrow gap between the pole-pieces of a pair of electromagnets, arranged to produce a very intense narrow magnetic field along two opposite radii. Fig. 365 shows its form, and the arrangement for collecting the current from the periphery, which is made up of 320 insulated pieces of copper strongly held together by an insulated steel ring at the middle of the rim. It gave, at 1500 revolutions per minute, a current of 2000 amperes at 25 volts; the entire machine weighing 1·1 tons.

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[1] See Fritsche's book, *Die Gleichstrom-Dynamomaschine*, Berlin, 1889; also Specification of British Patent, No. 13,080 of 1887. See also *The Electrician*, xxii. 655, 1888; also *Electrical Review*, xxix. 472, 1891; and *Electrical World*, xii. 205, 1889.

[2] *Journal de la Société Physico-chimique russe*, xxii. 135, 1890.

CHAPTER XX.

ELECTRIC MOTORS (CONTINUOUS CURRENT).

IN the first chapter, the definition was laid down that dynamo-electric machinery meant "machinery for converting energy in the form of mechanical power into energy in the form of electric currents, or *vice versâ.*" Having dealt with the dynamo in its function as a generator of electric currents, we now come to its converse function, namely, that of converting the energy of electric currents into the energy of mechanical motion.

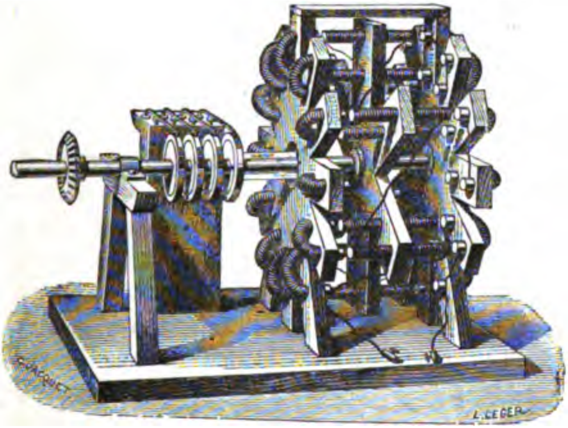
An *electric motor*, or, as it was formerly called, an *electro-magnetic engine*, is one which does mechanical work at the expense of electric energy; and this is true, no matter whether the magnets which form the fixed part of the machine be permanent magnets of steel or electromagnets. In fact, any kind of dynamo, whether for continuous currents or alternating currents, can be used conversely as a motor, though, as we shall see, some more appropriately than others.

Every one knows that a magnet will attract the opposite pole of another magnet, and will pull it round. We know also that every magnet placed in a magnetic field tends to turn round and set itself along the lines of force.

It is not, therefore, difficult to understand that very soon after the invention of the electromagnet, which gave us for the first time a magnet whose power was under control, a number of ingenious persons perceived that it would be possible to construct an electromagnetic engine, in which an electromagnet, placed in a magnetic field, should be pulled round; and, further, that the rotation should be kept up continuously, by cutting off or reversing the current at an appropriate moment. As a matter of fact, a mere coil of wire carrying a current, is acted upon when placed in the magnetic field, and is pulled round as a magnet is. On this very principle was constructed the earliest electric motor of Ritchie, so well known in many forms as a stock piece of electric apparatus, but little better in reality than a toy. Joule[1] also devised several forms of electric motor.

A great step in advance was made by Jacobi, who, in 1838, constructed the multipolar machine of which we give a representation in Fig. 366. This motor, which Jacobi designed for his electric boat, had two strong wooden frames, in each of which a dozen electromagnets were fixed, their poles being set alternately. Between them, upon a wooden disk, was placed another set of electromagnets, which, by the alternate attraction and repulsion of the fixed poles, were kept in rotation; the current which traversed the rotating magnets being regularly reversed at the moment of passing the poles of the fixed magnets by means of a commutator, consisting, according to Jacobi's directions, of four brass-toothed wheels having pieces of ivory or wood let in between the teeth for insulation. Jacobi's motor was, in fact, a very advanced type

FIG. 366.



JACOBI'S ELECTRIC MOTOR.

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[1] *Annals of Electricity*, ii. 222, 1838; and iv. 203, 1839.

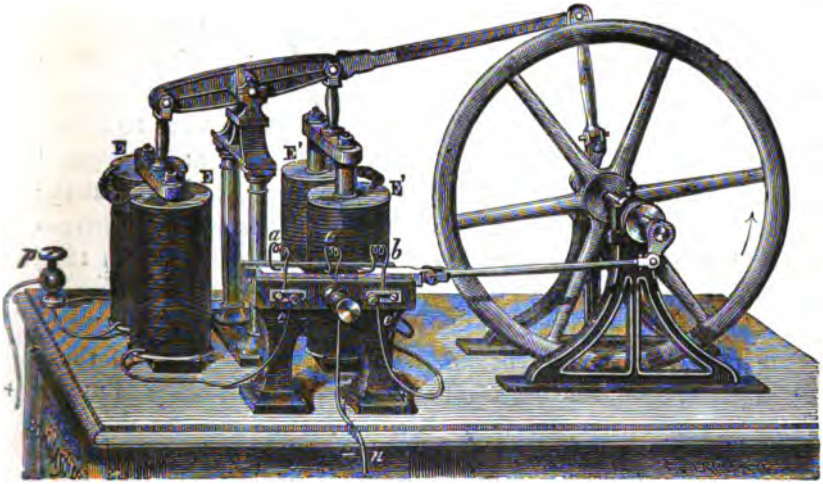
of dynamo, and would, of course, generate currents if driven round by mechanical power.

A still earlier rotating apparatus, and, like Ritchie's motor, a mere toy, was Sturgeon's wheel-disk, described in 1823. This instrument, interesting as being the forerunner of Faraday's disk dynamo, is the representative of a distinctive class of machines, namely, those which have a sliding contact merely, and need no commutator.

Another class of motors may be named, wherein the moving part, instead of rotating upon an axis, is caused to oscillate backwards and forwards. Professor Henry, to whom we owe so much in the early history of electromagnetism, constructed, in 1831, a motor with an oscillating beam, alternately drawn backwards and forwards by the intermittent action of an electromagnet. Dal Negro's motor of 1833 was of this class; in it a steel rod was caused to oscillate between the poles of an electromagnet, and caused a crank to which it was geared to rotate in consequence. A distinct improvement in this type of machine was introduced by Page, who employed hollow coils or bobbins as electromagnets, which, by their alternate action, sucked down iron cores into the coils, and caused them to oscillate to and fro. Motors of this kind form an admirable illustration of one of the laws of electromagnetics, first formulated by Gauss, but developed later by Maxwell, to the effect that a circuit acts on a magnetic pole in such a way as to make the number of magnetic lines of force that pass through the circuit a maximum.

Page's suggestion was further developed by Bourbouze, who constructed the curious motor depicted in Fig. 367, which looks uncommonly like an old type of steam engine. We have here a beam, crank, fly-wheel, connecting-rod, and even an eccentric valve-gear and a slide-valve. But for cylinders we have four hollow electromagnets; for pistons, we have iron cores that are alternately sucked in and drawn out; and, for slide-valve we have a commutator, which, by dragging a pair of platinum-tipped springs over a flat surface made of three pieces of brass separated by two insulating strips of ivory, reverses at every stroke the direction of the currents in the coils of the electromagnets. It is really a very ingenious machine, but, in point of efficiency, far behind all modern electric motors. Unfortunately, it does not do to design dynamo-electric machinery on the same lines as steam engines.

FIG. 367.



BOURBOUZE'S ELECTRIC MOTOR.

Yet another now obsolete class of electric motors owed its existence to Froment, who, fixing a series of parallel iron bars upon the periphery of a drum, caused them to be attracted, one after the other, by an electromagnet or electromagnets, and thus procured a continuous rotation.

Lastly, of the various historical types of motor we may enumerate a class in which the rotating portion is enclosed in an eccentric frame of iron, so that as it rotates it gradually approaches nearer. Little motors, working on this principle of "oblique approach," were invented by Wheatstone, and have long been used for spinning Geissler tubes, and other light experimental work. More recently, Trouvé and others have sought to embody this principle in motors of more ambitious proportions, but without securing any advantage; for it would be better to bring the armature close to the pole-pieces of the field-magnet.

It is impossible, within the limits of this work, to deal with a tithe of all the various stages of discovery and invention, or with many interesting and curious machines that have from time to time been tried. It might be told how Page, after inventing his machine in 1834, succeeded in 1852 in constructing a motor of such a size that he was able to drive a circular saw and a lathe by it. Space fails to describe the electric motor of Davidson, which, in 1842, enabled him to propel a carriage, at the speed of four miles an hour, between Edinburgh and Glasgow. An engine which was of 10 horse-power was built in 1849, by Sören Hjorth, at Liverpool.[1] Other inventions are alluded to in the Historical Notes at the beginning of this book. Two notable steps were the invention, in 1855, of the shuttle armature of Siemens, and in 1864 of the ring armature by Pacinotti. But the real development came after the commercial introduction of Gramme's dynamos in 1871, as engineers began to understand how two of these machines could be used—one as generator, the other as motor—to transmit power through a line. The modern dynamo, with its distinct organs the field-magnet and the armature, has superseded all the older types of motor.

All the earlier attempts to introduce electric motors came to nothing, for two reasons. Firstly, at that time there was no economical method of generating electric currents known; secondly, the great physical law of the conservation of energy was not fully recognized, and its all-important bearings upon the theory of electric machinery could not be foreseen.

While voltaic batteries were the only available sources of electric currents, economical working of electric motors was hopeless; for a voltaic battery wherein electric currents are generated by dissolving zinc in sulphuric acid is a very expensive source of power. To say nothing of the cost of the acid, the zinc—the very fuel of the battery—costs more than twenty times as much as coal, and is a far worse fuel; for whilst an ounce of zinc will evolve heat to an amount equivalent to 113,000 foot-pounds of work,[1] an ounce of coal will furnish the equivalent of 695,000 foot-pounds.

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[1] An excellent account of the early forms of electric motor, both European and American, is to be found in Martin and Wetzler's *The Electric Motor and its Applications*, third edition, 1891. All readers interested in the subject should also consult the paper on *Electro-magnetism as a Motive Power*, by the late R. Hunt in *Proc. Inst. Civil Engineers*, xvi., April 1857, together with the discussion that followed it, in which part was taken by Professor Thomson (now Lord Kelvin), Mr. (now Sir William) Grove, Professor Tyndall, Mr. Cowper, Mr. Smee, and Mr. Robert Stephenson. They should also consult Kapp's *The Electric Transmission of Power*.

The fact, however, which seemed most discouraging, and which, if rightly interpreted in accordance with the law of conservation of energy, would have been found to be (on the contrary) a most encouraging fact, was the following:—If a galvanometer was placed in the circuit with the electric motor and the battery, it was found that when the motor was running the battery was unable to force through the wires so strong a current as that which flowed when the motor was standing still. The faster the motor ran, the weaker did the current become. Now there are only two causes that can stop such a current flowing in a circuit; there must be either an obstructive resistance or else a counter electromotive-force. At first, the common idea was, that when the motor was spinning round, it offered a greater resistance to the passage of the electric current than when it stood still. The genius of Jacobi[2] enabled him, however, to discern that the observed diminution of current was really due to the fact that the motor, by the act of spinning round, began to work as a dynamo on its own account, and tended to set up a current in the circuit in the opposite direction to that which was driving it. The faster it rotated the greater was the counter electromotive-force (or "electromotive-force of reaction") which was developed. In fact, the theory of the conservation of energy requires that such a reaction should exist. Joule,[1] by further experiment, found that the counter electric action is proportional to the velocity of rotation and to the magnetism of the magnets.

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[1] A convenint way of regarding the economic question from the point of view of the cost of the voltaic battery is afforded by the following calculation. Supposing the electric motor to convert all the electric energy of the battery without loss into mechanical energy, the amount of zinc used per horse-power in one hour will be almost exactly two pounds divided by the volts of electromotive-force of the cell employed in the battery.

[2] *Mémoire sur l'application de l'élèctromagnétisme au mouvement des machines*, par M. H. Jacobi (Potsdam, 1835). On p. 45 of this memoir Jacobi points out that the motor, when set into rotation by the current of the battery, becomes by virtue of its motion a magneto-electric apparatus capable of generating a current in a counter-direction in the circuit; and to this he rightly attributes the limit of uniform speed obtained by the motor.

Two points are vital to the right understanding of the action of electric motors: (1) The propelling drag, (2) the counter electromotive-force. The first is that the real driving-force which propels the revolving armature is the drag which the magnetic field exerts upon the armature wires through which the current is flowing (or, in the case of deeply-toothed armatures, on the protruding teeth): the second is that the revolving armature generates a counter electromotive-force as its moving wires cut the magnetic lines.

The Propelling Drag.—In Chapter V., on the mechanical actions in armatures, the drag, which a magnetic field exerts on a conductor carrying a current, has been explained, and calculations about its magnitude given. In a generator the drag acts in a direction which opposes the rotation, and is, in fact, a counter-force or reaction against the driving force. In a motor the drag is the driving force, and produces the rotation.

The Counter Electromotive-force.—Let it be remembered that wherever in an electric circuit, current flows through some portion of the circuit in which there is an electromotive-force, the current will there either receive or give up energy according to whether the electromotive-force acts *with* the current or *against* it. This will be made clearer by Fig. 368, representing a circuit in which there are a dynamo and a motor. Each is rotating right-handedly, and therefore generates an electromotive-force tending upwards from the lower brush to the higher. In each case the upper brush is the positive one. But in the dynamo, where energy is being supplied to the circuit, the electromotive-force is in the same direction as the current; whilst in the motor where work is being done, and energy is leaving the circuit, the electromotive-force is in a direction which opposes the current.

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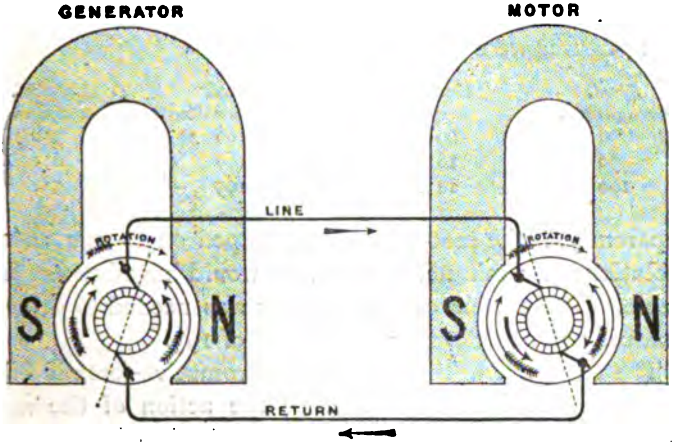
[1] *Annals of Electricity*, viii. 219, 1842, and *Scientific Papers*, p. 47.

There ought to be no difficulty in understanding that this electric reaction is an essential of motor working.

FIG. 368.



We know that in the converse case, when we are employing mechanical power to generate currents by rotating a dynamo, directly we begin to generate currents, that is to say, directly we begin to do electric *work*, it immediately requires much more power to turn the dynamo than is the case when no electric work is being done. In other words, there is an opposing reaction to the mechanical force which we apply in order to do electric work. An opposing reaction to a mechanical force may be termed a "counter-force." When, on the other hand, we apply (by means of a voltaic battery, for example) an electromotive-force to do mechanical work, we find that here again there is an opposing reaction; and an opposing reaction to an electromotive-force is a "counter electromotive-force."

The experiment of showing the existence of this counter electromotive-force is a very easy one. All one requires is a little motor, with a powerful field-magnet,[1] a few cells of battery of small internal resistance, and a galvanometer.

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[1] One of any ordinary type—a magneto-machine or a series-wound motor will answer.

They should be connected up in one circuit, and the deflexion of the galvanometer should be observed when the motor is held fast, and when it rotates with small and large loads. In an experiment made at the Technical College, Finsbury, on an Immisch motor, with separately-excited magnets, the following figures were obtained :—

Speed. Revs. per min.	*Current.* Amperes.	*Speed.* Revs. per min.	*Current.* Amperes.
0	20	160	7·8
50	16·2	180	6·1
100	12·2	195	5·1

Apparently, if the motor had been helped on to run at 261½ revolutions per minute, the current would have been reduced to zero. The current of 5·1 amperes was needed to drive the armature against friction at the speed of 195.

The existence of this counter electromotive-force is of the utmost importance in considering the action of the motor, because upon the existence and magnitude of this counter electromotive-force depends the degree to which any given motor enables us to utilize electric energy that is supplied to it in the form of an electric current. In fact, this counter electromotive-force is an absolute and necessary factor in the power of the motor, just as much as the velocity to which (*cæteris paribus*) it is proportional. Lieut. F. J. Sprague has made the suggestion to call it the "motor electromotive-force," thereby emphasizing the fact.

In discussing the dynamo as a generator, many considerations were pointed out, the observance of which would tend to improve the efficiency of such generators. It is needless to say that many of these considerations, such as the avoidance of useless resistances, unnecessary iron masses in cores, and the like, will also apply to motors. The freer a motor is from such objections, the more efficient will it be. But the efficiency of a motor in utilizing the energy of a current depends not only on its efficiency in itself, but on another consideration, namely the relation between the electromotive-force which it itself generates when rotating, and the electromotive-force or electric pressure at which the current is supplied to it. A motor which itself in running generates only a *low* electromotive-force cannot, however well designed, be an *efficient* or economical motor when supplied with currents at a *high* electromotive-force. A good low-pressure steam-engine does not become more "efficient" by being supplied with high-pressure steam. Nor can a high-pressure steam-engine, however well constructed, attain a high efficiency when worked with steam at low pressures. Analogous considerations apply to dynamos used as motors. They must be supplied with currents at electromotive-forces adapted to them. Even a perfect motor—one without friction or resistance of any kind—cannot give an "efficient" or economical result if the law of efficiency is not observed in the conditions under which the electric current is supplied to it.

ELEMENTARY THEORY OF ELECTRIC MOTIVE POWER.

It will be shown, mathematically, that the efficiency with which a perfect motor utilizes the electric energy of the current, depends upon the ratio between the counter electromotive-force developed in the armature of the motor and the electromotive-force of the current which is supplied by the battery. No motor ever succeeded in turning into useful work the whole of the currents that feed it, for it is impossible to construct machines devoid of resistance, and whenever resistance is offered to a current, part of the energy of the current is wasted in heating the wires that offer the resistance. Let the symbol W stand for the electric power supplied to an electric circuit by a battery or dynamo acting as a source; and let w stand for that part of the energy which the motor takes up as useful power from the circuit.[1] These symbols may stand for the numbers of *watts* respectively supplied and utilized. All that part of the energy of the current which is not utilized by the motor, and transformed into useful work, will be wasted in useless heating of the resistances. The heat-loss will therefore be equal to $W - w$.

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[1] The symbol w must be clearly understood to refer to the value of the work taken up by the motor, *as measured electrically*. The whole of this work will not appear as useful mechanical effect however, for part will be lost by mechanical friction, and part also in the wasteful production of eddy-currents in the moving parts of the motor. What proportion of w appears as useful mechanical work depends on the efficiency of the motor *per se*, which we are not here considering. In all that follows immediately we shall suppose such causes of loss not to exist, or the motor will be considered as a perfect motor.

But if we want to work our motor under the conditions of greatest economy, it is clear that we must have as little heat-waste as possible; or, in symbols, w must be as nearly as possible equal to W. It will be shown mathematically that the ratio between the useful energy thus appropriated and the total energy spent, is equal to the ratio between the counter electromotive-force of the motor and the whole electromotive-force of the battery that feeds the motor. (As it is not wished here to complicate general considerations by introducing into the expression for the efficiency the energy wasted in heat in the field-magnet coils of the motor, we here assume that the magnetism of the field-magnets is independently excited.) The proof will be given later. Let us call this whole electromotive-force with which the battery feeds the motor $\mathcal{E}$, and let us call the counter electromotive-force E. Then the rule is

$$\frac{w}{W} = \frac{E}{\mathcal{E}}.$$

But we may go one stage further. If the motor be prevented from turning, the current, as calculated by Ohm's law, would be

$$I = \frac{\mathcal{E}}{R}.$$

If the resistances of the circuit are constant, the current i, observed when the motor is running, will be less than I. But, from Ohm's law, we know that

$$i = \frac{\mathcal{E} - E}{R},$$

where R is the total resistance of the circuit. Hence

$$\frac{I - i}{I} = \frac{E}{\mathcal{E}} = \frac{w}{W}.$$

From which it appears that we can calculate the efficiency at which the motor is working, by observing the ratio between the fall in the strength of the current and the original strength. Now as this mathematical law of efficiency has been known for forty years, it is strange that, even in many of the accepted text-books, it was until lately ignored or misunderstood. Another law, discovered by Jacobi, not a law of efficiency at all, but a law of maximum work in a given time, has usually been given instead. A machine does not generally do its work with the best economy when it works furiously, performing the greatest work in the least possible time; and the maximum economy or efficiency of an electric motor is not when its output is at a maximum. Yet, strange to say, it was common ten years ago to find Jacobi's law of maximum power or activity stated as the law of maximum efficiency. Many electricians were consequently under the erroneous impression that a motor could never have a higher efficiency than 50 per cent.!

The true law of efficiency was clearly stated by Thomson in 1851, and is recognized in a paper by Joule at about the same date. See also Rankine's *Steam Engine*, p. 546. Professor Anthony, late of Cornell University, informs the author that he has taught the true law for the past fifteen years. Jacobi seems very clearly to have understood that his law was a law of maximum working, but not to have understood that it was not a law of true economical efficiency. In one passage (*Annales de Chimie et de Physique*, t. xxxiv. 1852, p. 480), he says:—"Le travail mécanique maximum, *ou plutôt l'effet économique*, n'est nullement compliqué avec ce que M. Müller appelle les circonstances spécifiques des moteurs électro-magnétiques." Yet, though there is here apparently a confusion between the two very different laws, in a preceding part of the very same memoir Jacobi says (p, 466):—"En divisant la quantité de travail par la dépense (de zinc), on obtient une expression très-importante dans la mécanique industrielle: c'est l'effet économique, ou ce que les Anglais appellent *duty*." Here, again, is a singular confusion. The definition is perfect; but "effet économique" is not the same thing as the maximum power. Jacobi's law is not a law of maximum efficiency, but a law of maximum power; and that is where the error creeps in. It is significant, in suggesting the cause of this remarkable conflict of ideas, that throughout this memoir Jacobi speaks of *work* as being the product of force and velocity, not of force and displacement. The same mistake—common enough amongst continental writers—is to be found in the accounts of Jacobi's law given in Verdet's *Théorie Mécanique de la Chaleur*, in Müller's *Lehrbuch der Physik*, and even in Wiedemann's *Galvanismus*. Now the product of force and velocity is not work, but work divided by time, that is to say "power," or "rate of working," or "activity." This may account for the widely-spread fallacy. Jacobi makes another curious slip in the memoir above alluded to (p. 463), by supposing that the strength of the current can only become = 0 when the motor runs *at an infinite speed.* We all know now that the current will be reduced to zero when the counter electromotive-force of the motor equals that of the external supply; and if this is finite the speed of the motor, if there is independent magnetism in its magnets, need also only be finite. This error—also to be found in Verdet—seems to have thrown the latter off the track of the true law of efficiency, and to have made him fall back on Jacobi's law. In a paper by Achard in the *Annales des Mines* in January 1879, a clear distinction is drawn between the maximum activity and the efficiency of a motor, and he points out how as the latter increases to a maximum, the former falls to zero. In April, Sir C. W. Siemens and Sir W. Thomson gave evidence on electric transmission before a Parliamentary Committee, the latter showing that it was possible to transmit 21,000 HP. through a copper wire ½-inch in diameter, to 300 miles, provided a potential of 80,000 volts was used. Later in the same year Professors Elihu Thomson and Houston, basing their remarks upon the suggestions of Sir W. Thomson and Siemens, proposed to obtain economic results by connecting in series several dynamos at one end of a line, and several motors at the other, so as to work with small currents and high electromotive-forces. The advantage of high voltage in both dynamo and motor at the two ends of the line was never better or more clearly put than by Prof. W. E. Ayrton, in his lecture on "Electric Transmission of Power," before the British Association, in Sheffield in August 1879. These high voltages he proposed to obtain not by increasing the magnetism but by increasing the speed, and by separate excitation of both dynamo and motor. The gain in economy by allowing the motor to run at a high speed with efficiency increasing as its speed increases, was also pointed out by Dr. Werner von Siemens in his address to the Naturforscher meeting in September 1879 (see Werner von Siemens *Wissenschaftlichen und Technischen Arbeiten*, vol. ii., p. 374).

Jacobi's law concerning the maximum power of an electric motor supplied with currents from a source of given electromotive-force is the following:—The mechanical work given out by a motor is a maximum when the motor is geared to run at such a speed that the current is reduced to half the strength that it would have if the motor was stopped. This, of course, implies that the counter electromotive-force of the motor is equal to half the electromotive-force furnished by the battery or generator. Now, under these circumstances, only half the energy furnished by the external source is utilized, the other half being wasted in heating the circuit. If Jacobi's law was indeed the law of efficiency, no motor, however perfect in itself, could convert more than 50 per cent. of the electric energy supplied to it into actual work.

Dr. Siemens, who first made us realize the true physical signification of the mathematical expressions which, until then, had been regarded as mere abstractions, showed, some years ago, that a dynamo can be, in practice, so used as to give out more than 50 per cent. of the energy of the current. It can, in fact, work more efficiently if it be not expected to do its work so quickly, while using so much current. In fact, if the motor be arranged so as to do its work at less than the maximum rate, by being geared so as to do much less work per revolution, but yet so as to run at a higher speed, it will be more efficient; that is to say, though it does less work, there will also be still less electric energy expended, and the ratio of the useful work done to the energy expended will be nearer unity than before. Or, instead of gearing it up to run fast, we may gain the same advantage by strengthening its field-magnets.

Theory of Motors.—If $\mathcal{E}$ be the electromotive-force of the mains supplying the current to the motor when the motor is at rest, and i be the current which flows at any time, the whole electric power W expended in unit time will be expressed in watts, as the product of the whole of the applied volts multiplied by the whole of the amperes, or:—

$$\text{(Total watts) } W = \mathcal{E}\, i = \mathcal{E}\,\frac{(\mathcal{E} - E)}{R}. \qquad \text{[I.]}$$

Now, when the motor is running, part of this electric power is being spent in doing work, and the remainder is wasting itself in heating the wires of the circuit. The useful part may be similarly written down, as the product of the armature's own volts (the counter electromotive-force) and the amperes, or:—

$$\text{(Useful watts) } w = \mathrm{E}\, i = \mathrm{E}\, \frac{(\mathcal{E} - \mathrm{E})}{\mathrm{R}}. \qquad \text{[II.]}$$

All the power which is not thus utilized is wasted in heating the resistances. So we may write:—

Power supplied = power utilized + power wasted in heating.

or,

$$\mathrm{W} = w + \text{watts wasted in heating.}$$

But, by Joule's law, the heat-waste of the current whose strength is i running through resistance R, is expressed by the equation

$$= i^2\, \mathrm{R} \text{ (watts).}$$

Substituting this value above, we get

$$\mathrm{W} = w + i^2\, \mathrm{R},$$

Comparing equation [I.] with equation [II.], we get the following:—

$$\frac{w}{\mathrm{W}} = \frac{\mathrm{E}\,(\mathcal{E} - \mathrm{E})}{\mathcal{E}\,(\mathcal{E} - \mathrm{E})};$$

or, finally

$$\frac{w}{\mathrm{W}} = \frac{\mathrm{E}}{\mathcal{E}}. \qquad \text{[III.]}$$

This is, in fact, the mathematical law of efficiency, so long misunderstood until Siemens showed its practical significance. We may appropriately call it *the law of Siemens.* Here the ratio $\frac{w}{\mathrm{W}}$ is the measure of the efficiency of the motor, and the equation shows that we may make this efficiency as nearly equal to unity as we please, by so adjusting either the magnetism of the field-magnets or the speed of the motor that E is very nearly equal to $\mathcal{E}$.

Now the power utilized is equal to the difference between the total power supplied and the part wasted in heat, or in symbols :—

$$w = \mathcal{E} i - i^2 R. \qquad \text{[IV.]}$$

In order to find what value of i will give us the maximum value for w (which is the work done by the motor *in unit time*), we must take the differential coefficient and equate it to zero.[1]

$$\frac{dw}{di} = \mathcal{E} - 2 i R = 0,$$

$$\mathcal{E} - 2 i R - 0$$

whence we have

$$i = \tfrac{1}{2} \frac{\mathcal{E}}{R}.$$

But, by Ohm's law, $\frac{\mathcal{E}}{R}$ is the value of the current when the motor stands still. So we see at once that, to get maximum work per second out of our motor, the motor must run at such a speed as to bring down the current to half the value which it would have if the motor were at rest. In fact, we here

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[1] The argument can be proven, though less simply, without the calculus, as follows : write equation [IV.] in the following form :

$$i^2 R - \mathcal{E} i + w = 0.$$

Solving this as an ordinary quadratic equation, in which i is the unknown quantity, we have

$$i = \frac{\mathcal{E} \pm \sqrt{\mathcal{E}^2 - 4 R w}}{2 R}.$$

To find from this what value of i corresponds to the greatest value of w, it may be remembered that a negative quantity cannot have a square root, and that therefore the greatest value that w can possibly have will occur when

$$4 R w = \mathcal{E}^2,$$

for then the term under the root sign will vanish. When this condition is observed it will follow that

$$i = \frac{\mathcal{E}}{2 R},$$

or the current will be reduced to half its original value.

prove the law of Jacobi for the maximum rate of doing work. But here, since

$$i = \frac{\mathcal{E} - \mathrm{E}}{\mathrm{R}} = \tfrac{1}{2}\frac{\mathcal{E}}{\mathrm{R}},$$

it follows that

$$\mathcal{E} - \mathrm{E} = \tfrac{1}{2}\,\mathcal{E},$$

or

$$\frac{\mathrm{E}}{\mathcal{E}} = \tfrac{1}{2};$$

whence it follows also that

$$\frac{w}{\mathrm{W}} = \tfrac{1}{2}.$$

That is to say, the efficiency is but 50 per cent. when the motor does its work at the maximum rate.[1]

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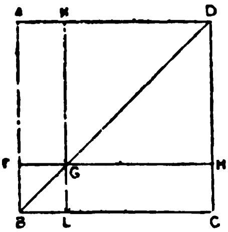
[1] It may be worth while to recall a precisely parallel case that occurs in calculating the currents from a voltaic battery. Every one is familiar with the rule for grouping a battery which consists of a given number of cells, that they will yield a maximum current through a given external resistance when so grouped that the internal resistance of the battery shall, as nearly as possible, equal the external resistance. But this rule, which is true for maximum current (and, therefore, for maximum rate of using up the zinc of one's battery), is not the case of greatest economy. For if external and internal resistance are equal, half the energy of the current will be wasted in the heat of the cells, and half only will be available in the external circuit. If we want to get the greatest economy, we should group our cells so as to have an internal resistance much less than the external. We shall not get so strong a current, it is true; and we shall use up our zincs more slowly; but a far greater proportion of the energy will be expended usefully, and a far less proportion will be wasted in heating the battery cells. The maximum economy will, of course, be got by making the external resistance infinitely great as compared with the internal resistance. Then all the energy of the current will be utilized in the external circuit, and none wasted in the battery. But it would take an infinitely long time to get through a finite amount of work in this extreme case. The same kind of reasoning is strictly applicable to dynamos used as generators, the resistance of the rotating part of the circuit being the counterpart of the internal resistance of the battery cells. For good economy the resistance of the armature should be very low as compared with that of the external circuit.

GRAPHIC REPRESENTATION OF LAWS OF MOTORS.

Several graphic constructions have been suggested to convey these facts to the eye; one of these enables us, in one diagram, to exhibit graphically both the law of maximum rate of working, and the law of efficiency.[1]

Let the vertical line, A B (Fig. 369), represent the electromotive-force $\mathcal{E}$ of the electric supply. On A B construct a square A B C D, of which let the diagonal B D be drawn. Now measure out from the point B, along the line B A, the counter electromotive-force E of the motor. The length of this quantity will increase as the velocity of the motor increases. Let E attain the value B F. Let us inquire what the actual current will be, and what the energy of it; also what the work done by the motor is. First complete the construction as follows:—Through F draw F G H, parallel to B C, and through G draw K G L, parallel to A B. Then the actual electromotive-force at work in the machine producing a current is $\mathcal{E} - E$, which may be represented by any of the lines A F, K G, G H, or L C. Now the electric energy expended per second is $\mathcal{E} i$; and since $i = \frac{\mathcal{E} - E}{R}$, it may be written as

FIG. 369.



$$\frac{\mathcal{E}(\mathcal{E} - E)}{R};$$

and the electric energy utilized by the motor, measured in *watts*, is

$$\frac{E(\mathcal{E} - E)}{R}.$$

R being a constant, the values of the two may be written respectively

$$\mathcal{E}(\mathcal{E} - E) \text{ and } E(\mathcal{E} - E).$$

---

[1] See paper by the author in the *Philosophical Magazine*, Feb. 1883.

Now the area of the rectangle

$$\mathrm{A\,F\,H\,D} = \mathcal{E}\,(\mathcal{E} - \mathrm{E}),$$

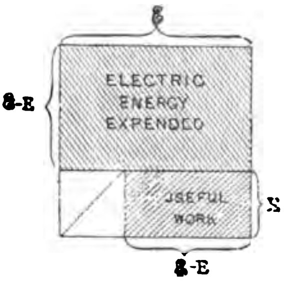
and that of the rectangle

$$\mathrm{G\,L\,C\,H} = \mathrm{E}\,(\mathcal{E} - \mathrm{E}).$$

The ratio of these two areas on the diagram is the efficiency of a perfect motor, under the condition of a given constant electromotive-force in the electric supply.

Turn to Fig. 370, in which these areas are shaded. This figure represents a case where the motor is too heavily loaded, and can turn only very slowly, so that the counter electromotive-force E is very small compared with $\mathcal{E}$. Here the area which represents the energy expended, is very large; while that which represents useful work realized in the motor is very small. The efficiency is obviously very low. Two-thirds or more of the energy is being wasted in heat.

FIG. 370.



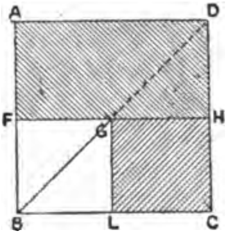
So far we have assumed that the efficiency of a motor (working with a given constant external electromotive-force) is to be measured electrically. But no motor actually converts into useful mechanical effect the whole of the electric energy which it absorbs, since part of the energy is wasted in friction and part in wasteful electro-magnetic reactions between the stationary and moving parts of the motor. What we are expressing thus as useful work is the work actually delivered to the armature to drive it. It is a mere matter of good engineering how small a percentage of this must be discounted for friction in the bearings, eddy-currents, hysteresis, and the like. If, however, we might consider the motor to be a *perfect* engine (devoid of friction, not producing wasteful eddy-currents, running without sound, giving no sparks at the collecting-brushes, &c.), then we might take the mechanical output as being precisely equal to the actual power delivered electrically to the armature. Such a "perfect" electric engine would, like the ideal "perfect" heat engine of Carnot, be perfectly reversible. In Carnot's heat engine it is supposed that the whole of the heat actually absorbed in the cycle of operations is converted into useful work; and in this case the efficiency is the ratio of the heat absorbed to the total heat expended. As is well known, this efficiency of the perfect heat engine can be expressed as a function of two absolute temperatures, namely those respectively of the heater and of the refrigerator of the engine. Carnot's engine is also ideally reversible; that is to say, capable of reconverting mechanical work into heat.

The mathematical law of efficiency of a perfect electric engine illustrated in the above construction is an equally ideal case; and the efficiency can also be expressed, when the constants of the case are given, as a function of two electromotive-forces. We shall return to this comparison a little later.

The Law of Maximum Activity.

Let us next consider the area G L C H of the diagram (Fig. 371), which represents the work utilized in the motor. The value of this area will vary with the position of the point G, and will be a maximum when G is midway between B and D; for of all rectangles that can be inscribed in the triangle B C D, the square will have maximum area (Fig. 371). But if G is midway between B and D, the rectangle G L C H will be exactly half the area of the rectangle A F H D; or, the useful work is equal to half the energy expended. When this is the case, the counter electromotive-force reduces the current to half the strength it would have if the motor were at rest; which is Jacobi's law of the efficiency of a motor doing work at its greatest possible rate. Also F will be half-way between B and A, which signifies that $E = \frac{1}{2} \mathcal{E}$.

Fig. 371.

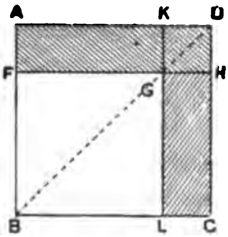


Geometric Illustration of Jacobi's Law of Maximum Activity.

Law of Maximum Efficiency.

Again, consider these two rectangles when the point G moves indefinitely near to D (Fig. 372). We know from common geometry that the rectangle G L C H is equal to the rectangle A F G K. The area (square) K G H D, which is the excess of A F H D over A F G K, represents therefore the electric energy which is wasted in heating the resistances of the motor. That the efficiency should be a maximum the heat-waste must be a minimum.

FIG. 372.



GEOMETRIC ILLUSTRATION OF THE LAW OF MAXIMUM EFFICIENCY.

In Fig. 369 this corner square, which stands for the heat-waste, was enormous. In Fig. 371 it was exactly half the energy. In Fig. 372 it is only about one-eighth. Clearly, we may make the heat-waste as small as we please, if only we will take the point F very near to A. The efficiency will be a maximum when the heat-waste is a minimum. The ratio of the areas G L C H and A F H D, which represents the efficiency, can therefore only become equal to unity when the square K G H D becomes indefinitely small—that is, when the motor runs so fast that its counter electromotive-force E differs from $\mathcal{E}$ by an indefinitely small quantity only.

It is also clear that if our diagram is to be drawn to represent any given efficiency (for example, an efficiency of 90 per cent.), then the point G must be taken so that area G L C H $= \frac{9}{10}$ area A F H D; or, G must be $\frac{9}{10}$ of the whole distance along from B towards D. This involves that E shall be equal to $\frac{9}{10}$ of $\mathcal{E}$, or that the motor shall run so fast as to reduce the current to $\frac{1}{10}$ of what it would be if the motor were standing still. Thus we verify, geometrically, the law of maximum efficiency. If there is leakage in the line, then, as Professor Oliver Lodge and Mr. G. Kapp[1] have pointed out, this law will require modification, for the higher the counter electromotive-force of the motor, the higher will be the potential of the line and the greater the loss by leakage.

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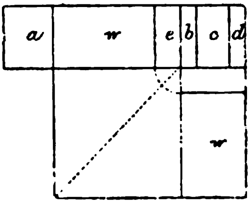
[1] See Kapp's *Electric Transmission of Energy* (1886), p. 165.

Further, if the motor be not a "perfect" one, but one whose intrinsic efficiency, or *efficiency per se*, is known, the actual mechanical work performed by the motor can be represented on the diagram by simply retrenching from the rectangle G L C H the fraction of work lost in friction, &c. Similarly, in the case where the electric energy expended has been generated in a dynamo-electric machine whose intrinsic efficiency is known, the total mechanical work expended can be represented by adding on to the area A F H D the proportion spent on useless friction, &c. To make the diagram still more expressive we may divide the area K G H D into slices proportional to the several resistances of the circuit; and the areas of these several slices will represent the heat wasted in the respective parts of the circuit. These points are exemplified in Fig. 373, which represents the transmission of power between two dynamos, each supposed to have an intrinsic efficiency of 80 per cent., each having 500 ohms resistance, working through a line of 1000 ohms resistance, the electromotive-force of the machine used as generator being 2400 volts, and the counter electromotive-force of the machine used as motor being 1600 volts.

FIG. 373.



The entire upper area represents the total mechanical work expended. Call this 100. It is expended as follows:— $a = 20$, lost by friction, &c., in the generator; $b = 6\frac{2}{3}$, lost in heating generator; $c = 13\frac{1}{3}$, lost in heating line-wires; $d = 6\frac{2}{3}$, lost in heating motor; $e = 10\frac{2}{3}$, lost in friction in the motor; $w = 42\frac{2}{3}$ is the percentage realized as useful mechanical work.

When the mechanical losses are thus taken into account it becomes evident at once that the maximum efficiency will be at some value of E less than $\mathcal{E}$. This is considered further in Chapter XXVI. on the Transmission of Power.

It is now evident what we have to do to obtain any desired percentage of efficiency. Suppose current is supplied at 100 volts at the mains: then to utilize 90 per cent., we must employ as motor a dynamo which, when running at its proper speed and output, generates an electromotive-force of 90 volts.

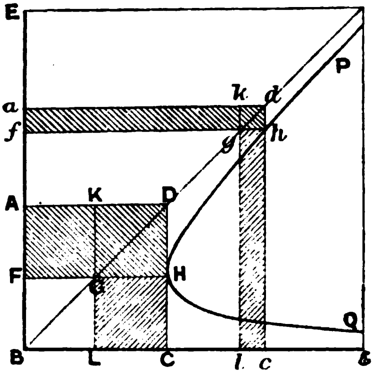
We may now extend the graphic method to two further cases.

Suppose that $\mathcal{E}$ is no longer taken as a constant, but that the work to be done by the motor per second is a constant. For this case we may write equation [II.], p. 562, as

$$E(\mathcal{E} - E) = wR.$$

This equation is graphically represented by the curve P H Q (Fig. 374), in which the values of $\mathcal{E}$ are plotted as abscissæ and those of E as ordinates. From this curve it is at once seen that there will be a certain minimum value of $\mathcal{E}$ which will suffice to give to the motor the prescribed amount of energy per second. The curve is so drawn that it passes through the corner H of all the areas equal to G L C H drawn to fit under the diagonal of the square. Of these areas, which represent equal work done by the motor, the one which has minimum value of $\mathcal{E}$ is the square which fits to the apex of the curve and corresponds to the case where $\mathcal{E} = 2E$. This result, which was first pointed out by Prof. Carhart,[1] is the converse of Jacobi's law, and, like it, involves an efficiency of only 50 per cent. A much higher efficiency is obtained when $\mathcal{E}$ and E are both greater, as indicated by the square drawn through the point *h*.

FIG. 374.



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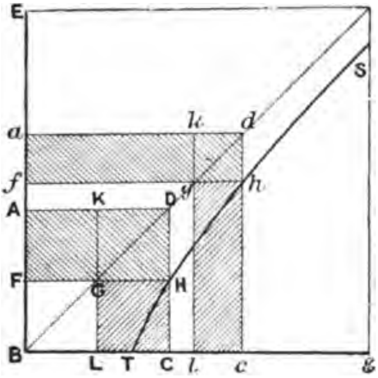
[1] *American Journal of Science*, xxxi. 95, 1886.

Again, suppose that W, the work supplied electrically, is maintained constant; for this case (Fig. 375) we may write equation [I.], p. 561, in the form

$$\mathcal{E}\,(\mathcal{E} - \mathrm{E}) = \mathrm{W\,R},$$

giving us the curve T H S. In this case $\mathcal{E}$ is a minimum when E is zero, and all the work is wasted in heat; and *w*, the work of the motor, is a maximum only when both $\mathcal{E}$ and E are infinitely great. This result is also due to Carhart.

FIG. 375.



It only remains to point out a curious contrast that presents itself between the efficiency of a perfect heat engine and that of a perfect electric engine. We saw that the one could be expressed as a function of two temperatures, whilst the other could be expressed as a function of two electromotive-forces. But in the heat engine the efficiency is the greatest when the difference between the two temperatures is a maximum; whilst in the electric engine the efficiency is the greatest when the difference between the two electromotive forces is a minimum. The two cases are contrasted in Figs. 376 and 377, Fig. 376 showing the efficiency of a heat engine working between temperatures T and *t* (reckoned from absolute zero); whilst Fig. 377 shows the efficiency of an electric engine receiving current at an electromotive-force $\mathcal{E}$, its counter electromotive-force being E. Joule's remark, here illustrated, that an electric engine may be readily made to be a far more efficient engine than any steam-engine, is amply justified by all experience. The rapid extension in the use of electric motors, large and small, which has taken place during the past few years, proves that where power can be produced sufficiently cheaply on the large scale, either from natural sources, such as water-power, or by large steam-engines burning cheap coal, such power can be electrically distributed to small motors (not exceeding a few horse-power) with an economic

FIG. 376.

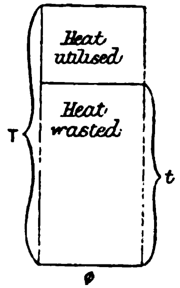
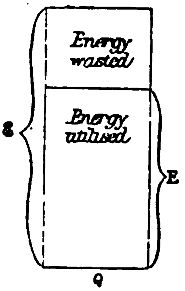


FIG. 377.



HEAT ENGINE AND ELECTRIC ENGINE CONTRASTED.

result; for the cost of erecting, maintaining, and supplying the electric power to such motors is less than the cost of erecting, maintaining, and supplying fuel and water to small steam-engines of equal power.

SPEED AND TORQUE OF MOTORS.

Certain very important relations subsist between the condition of the electric supply and the speed and turning-moment of a motor.

In Chapter V., on Mechanical Actions and Reactions, it was set forth that the power transmitted along a shaft is the product of two factors, the speed and the torque (or turning-moment). If ω stands for the angular velocity and T for the torque,[1] then

$$\omega\,\mathrm{T} = \text{mechanical work per second, or power.}$$

---

[1] If n be the number of revolutions per *second*, then $2\,\pi\,n = \omega$. Also if F be the transmitted pull on the belt (or rather the difference between the pull in that part of the belt which is approaching the driving pulley and the pull in that part which is receding from the driving pulley) in pounds weight, and r be the radius of the pulley, $\mathrm{F}\,r$ = the turning-moment or torque = T, then $\omega\,\mathrm{T} = 2\,\pi\,n\,r\,\mathrm{F}$ = the number of foot-pounds per second transmitted by the belt. This may also be

This may be expressed in watts by use of the proper coefficient.

Now if E is the electromotive-force generated by the armature, and i the current through it, the electric energy per second in the armature is the product;—

$$E\,i = \text{electric work per second (in watts}^1\text{)}.$$

If the whole of these four quantities, ω, T, E, and i, are armature quantities, strictly, we may equate the electrical and mechanical expressions together; and the equation will be true for either a motor or a generator. In the generator, E and i are in the same direction and T opposes ω; or there is a counter-torque. In the motor, T and ω are in the same direction, but E opposes i; or there is a counter-electromotive-force.

In treating of the dynamo as a generator, it was assumed that the mechanical power could be supplied under one of the two standard conditions, on the one hand of *constant speed* (and torque varying with the electrical output), or else on the other (p. 130) of *constant torque* (and speed varying with the output). One of these two conditions being prescribed, algebraic expressions had then to be found for the two corresponding factors of the electric output, namely the *electromotive force* and the current, under varying conditions of resistance in the circuit. Also we investigated these conditions which would result in making one or other factor of the electric

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proved as follows: Horse-power is product of the force into the velocity. The circumference of the pulley is $2\pi r$, and it turns n times per second, therefore the circumferential velocity is $2\pi r n$, and this, multiplied by F, gives the work per second. If F is expressed in grammes weight, and r in centimetres, then $2\pi r n$ F will give the power in gramme-centimetres, and must be divided by $7 \cdot 6 \times 10^6$ to bring it to horse-power, and must be multiplied by 981×10^{-7} to bring it to watts. If ω is in radians per second and T in centimetre-dynes, then the product will be in ergs per second, and can be brought to watts by dividing by 10^7.

[1] Since 1 volt $= 10^8$ C.G.S. units of electromotive-force, and 1 ampere $= 10^{-1}$ C.G.S. units of current, 1 watt (or volt-ampere) will be $= 10^7$ C.G.S. units of work per second $= 10^7$ ergs per second $= 10^7 \div 981$ gramme-centimetres per second.

output constant. It was found convenient to study the relation between the two factors of output by the aid of the curves known as *characteristics.*

Similarly, in treating the dynamo as a motor, it will be assumed that such arrangements of electric supply can be made that the electric power can be furnished under one of the two standard conditions, on the one hand of *constant potential* (and current varying with the mechanical output of the motor), or on the other of *constant current* (and potential varying with the mechanical output). One of these two conditions being prescribed, we shall then have to find algebraic expressions for the two corresponding factors of the mechanical output, namely the *speed* and the *torque,* under varying conditions of load on the shaft. Also, we shall investigate what are the conditions which will result in making one or other factor of the mechanical output constant: in other words, we shall ascertain what are the conditions of self-regulation to make the motor run at constant speed or with constant torque. Lastly, it will be found convenient to study the relation between speed and torque by the aid of curves, which, by analogy, we may call *mechanical characteristics.*

GENERAL EXPRESSIONS FOR TORQUE AND SPEED.

The work imparted per second to the shaft of the motor may be expressed either in electrical or mechanical measure. In the former case it is the product of the motor's electromotive-force (i. e. the counter electromotive-force opposing the electromotive-force of supply) into the current flowing the armature; in the latter case it is the product of angular speed into torque. So we may write

$$w = \mathrm{E}\, i_a = \omega \mathrm{T} = 2\pi n \mathrm{T};$$

and (average) $\mathrm{E} = n\,\mathrm{C}\,\mathrm{N}$ exactly as in a dynamo that is being used as a generator (see p. 211). Hence

$$2\pi n \mathrm{T} = n\,\mathrm{C}\,\mathrm{N}\, i_a,$$
$$2\pi \mathrm{T} = \mathrm{C}\,\mathrm{N}\, i_a;$$

and finally the average value of the torque will be

$$T = i_a \frac{C\,\mathsf{N}}{2\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad [a].$$

From this it appears that if N is constant, the torque is simply proportional to the current in the armature.

To develop this expression further, we must remember that i can be calculated in terms of the electromotive-force of supply $\mathcal{E}$, as measured at the terminals of the machine, and the internal resistance of the circuit through the armature part, which we call r; and then

$$i_a = \frac{\mathcal{E} - E}{r};$$

whence it follows that

$$T = \frac{C\,\mathsf{N}}{2\pi} \cdot \frac{\mathcal{E} - n\,C\,\mathsf{N}}{r} \quad . \quad . \quad . \qquad [\beta].$$

From this it follows that when the speed becomes so great that $n\,C\,\mathsf{N} = \mathcal{E}$, there will be no torque. In fact, when there is no resisting force on the shaft the motor runs empty at its highest speed, namely, such as will make the counter electromotive-force as nearly as possible equal to the electromotive-force of supply. The maximum value of T, supposing N constant, is obviously when $n = 0$.

An expression for the speed can be obtained from the preceding:

$$2\pi T r = C\,\mathsf{N}\,\mathcal{E} - n\,C^2\,\mathsf{N}^2;$$

$$n = \frac{\mathcal{E}}{C\,\mathsf{N}} - \frac{2\pi T r}{C^2\,\mathsf{N}^2} \quad . \quad . \quad . \qquad [\,\gamma\,].$$

In equation [α] T will be expressed in dyne-centimetres if i_a is in absolute units of current (see p. 18); if i_a is given in amperes, then the value must be divided by 10 if T is to be obtained in dyne-centimetres, or by 9810 if it is to be obtained in gramme-centimetres, or by $13{\cdot}56 \times 10^7$ if the torque is to be expressed in pound-feet (i.e. so many pounds weight acting at a radius of one foot).

In equation [γ], in order that n may be expressed in revolutions per second, the value of $\mathcal{E}$, if given in volts, must be multiplied by 10^8; that of r, if in ohms, by 10^9; whilst T must be reduced to dyne-centimetres. If T is given in pound-feet, its value must be multiplied by $1{\cdot}356 \times 10^7$.

[Examples:—(1) In one of Brown's 4-pole machines used as motor $C = 368$; $i_a = 275$; giving 250 HP. at 500 revs. per minute. Calculate the number of magnetic lines that must go through the armature. (2) A 2-pole motor is required to supply 4 HP. in an arc-light circuit in which the current is kept at 10 amperes: How many volts must it generate? Assume $N = 2{,}000{,}000$, and that the speed is 15 revs. per second, how many armature conductors must it have?]

[The three equations [a], [β], and [γ] are true, not only for motors, but for generators, the $\mathcal{E}$ of the formulæ being in the latter case replaced by e. This will give negative values for T, the significance of the sign being that the torque due to the action of the magnetic field on the conductors carrying the armature current is such as to oppose the driving.]

It will be noticed that if only r is very small, and N relatively very large, the second term may be neglected, and the speed will then depend on the first term only. It will be the smaller as N is greater: this being the simple converse of the corresponding fact that the more powerful the magnetic field the less need be the speed of the dynamo to give the desired output. We may also notice that if N is constant, the speed is proportional to $\mathcal{E}$: it will be constant if the condition of supply is that of constant potential, but will be variable if $\mathcal{E}$ varies. Another important point is that, if a motor is to do its work at a slow speed, C should be great as well as N.

We must next inquire how n and T are affected by the fact that the value of N depends upon the construction and winding of the field-magnet of the motor, and by the conditions of supply. We shall consider the following kinds of machine:—

A. *Magneto Motor* and *Separately-excited Motor.*
B. *Series-wound Motor.*
C. *Shunt-wound Motor.*
D. *Compound-wound Motor.*

In each instance we shall have to take into account the conditions of supply, according as $\mathcal{E}$ or i is constant.

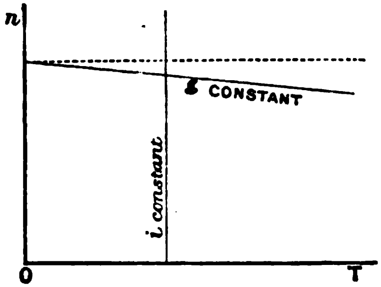
MAGNETO MOTOR AND SEPARATELY-EXCITED MOTOR.

It is here assumed that N is constant, in other words, that the perturbing reactions of the armature may be neglected. This will only be true when the lead at brushes is nearly zero, and the field-magnet powerful. Under these circumstances the general formulæ already found require small modification. The only internal resistance is that of the armature r_a.

Case (i.): $\mathcal{E}$ *constant.*

In this case formula [γ] gives the desired relation, from which the *mechanical characteristic* may be plotted out, as in Fig. 378. It is a straight line cutting the axis of n at a point representing to scale that speed at which n C N = $\mathcal{E}$; and it slopes downwards at an angle such that the tangent of the slope is equal to $2\pi r_a \div C^2 N^2$, or is proportional to the internal resistance. In the case of the separately excited motor, increase in the exciting current, strengthening the field, will obviously make the sloping line more nearly horizontal, as well as lowering the speed as a whole.

FIG. 378.



MECHANICAL CHARACTERISTICS OF MAGNETO MOTOR.

If we attempt to take into account the reactions of the armature, we must remember that the effect of the armature current is to demagnetize, if there is a backward lead, and to magnetize if there is a forward lead. A backward lead, then, would tend to make the sloping line, at constant $\mathcal{E}$, rise and become more level as the torque increased, because it would weaken the magnet, and so let the speed increase; whilst a forward lead would tend to make it slope still more.

Practical Determination of the Proper Potential for Given Motor.

Suppose a motor having a certain steel magnet and a certain armature be given, and let it be required to determine the potential at which it will give a certain speed. Run the motor on open circuit as a generator at the given speed, and observe the potential at its terminals. That is the number of volts $\mathcal{E}$ with which it must be supplied.

Case (ii.): *i constant.*

In this case, as reference to formula [*a*] shows, the torque is constant, being independent of speed and of internal resistance. The mechanical characteristic of the machine under these conditions is a vertical straight line.

SERIES MOTOR.

The fundamental equations are as before, with the addition of the following:—

$$r = r_a + r_m;$$

but now we may with advantage introduce the approximate formula for the law of the electromagnet (derived from Frölich's) given in Chapter VI., and write, as on p. 166, where i' is the diacritical current,

$$\mathsf{N} = \overline{\mathsf{N}} \frac{i}{i + i'}.$$

Putting this value of N into the expression [*a*], on p. 567, for the torque, and writing for brevity $\frac{C\overline{\mathsf{N}}}{2\pi} = Y$, we have

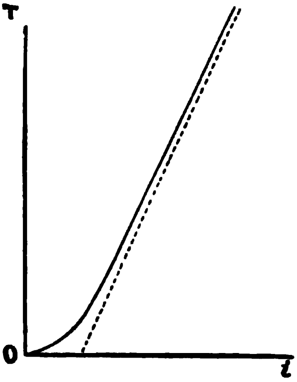
$$T = Y \frac{i^2}{i + i'}.$$

This relation between torque and current is given graphically in Fig. 379. For values of i that are small as compared with

i', T varies nearly as i^2; whilst for large values of i, as magnetic saturation advances, T is nearly proportional to i. The equation may also be written in the quadratic form

$$i^2 - \frac{T}{Y} i - \frac{T}{Y} i' = 0,$$

FIG. 379.



the solution of which is

$$i = \frac{T}{2Y}\left\{ 1 \pm \sqrt{1 + \frac{4Y}{T} i'} \right\}$$

Now from the expression given above we have

$$n = \frac{\mathcal{E} i}{2\pi T} - \frac{r i^2}{2\pi T};$$

$$n = \frac{\mathcal{E} i}{2\pi T} - \frac{r(i + i')}{2\pi Y};$$

and inserting the value of i as above

$$n = \frac{\mathcal{E}}{4\pi Y}\left\{ 1 + \sqrt{1 + \frac{4Y}{T} i'} \right\} - \frac{rT}{4\pi Y^2}\left\{ 1 + \sqrt{1 + \frac{4Y}{T} i'} \right\} - \frac{r i'}{2\pi Y}$$

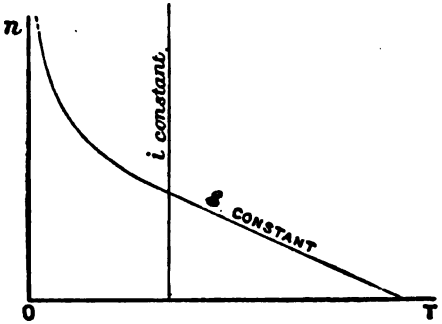
To simplify this hyperbolic expression, it is permissible for large values of T to neglect the second term under the root sign, giving approximately,

$$n = \frac{\mathcal{E} - r i'}{2\pi Y} - \frac{rT}{4\pi Y^2}.$$

Case (i.) : $\mathcal{E}$ *constant.*

If $\mathcal{E}$ is constant, then, as the last equation shows, for large values of T the values of n are equal to a certain constant less a quantity proportional to T ; or the mechanical characteristic at this point (when the magnets are well saturated) is, for all large values of T, approximately a straight line as shown in Fig. 380.

FIG. 380.



MECHANICAL CHARACTERISTICS OF SERIES MOTOR.

Case (ii.) : *i constant.*

Here, clearly, saving for secondary effects, the magnetization will be constant ; hence the torque will also be constant, as in Fig. 380. With a load exceeding a certain amount, the motor will not start; with a lesser load it will race until friction and eddy-currents make up the difference.

The properties of series-wound motors are so important that we may pause to consider them a little more fully. We know that if the current running through a series dynamo be constant, so that its magnetism is constant, the electromotive-force it develops is almost exactly proportional to its speed. It therefore follows that if E is proportional to ω, T will be proportional to i. This is abundantly verified in the case of series motors by experiments. When a Siemens series dynamo was arranged to lift a load of 56 lbs. on a hoist, is lifted this load at the rate of 212 feet per minute, developing a counter electromotive-force of 108·81 volts. The applied electromotive-force was 111 volts, and the resistance of the circuit was 0·3 ohm. The effective electromotive-force was therefore 2·19 volts and the current 7·3 amperes. When the resistance of the circuit was increased to 2·2 ohms, the speed fell to 169 feet per minute, the counter electromotive-force to 94·94; the effective electromotive-force, $\mathcal{E} - E$, was therefore 16·06 volts, and the current 7·3 amperes as before. When 4·8 ohms were inserted, the speed fell to 141 feet per minute, and E to 76 volts; $\mathcal{E} - E$ was 35 volts, and the current 7·3 amperes as before. *With the same load, the same current,* whatever the speed. The figures given on p. 556, relative to the Immisch motor also illustrate this point. The speed of a given series-wound motor depends solely on the electromotive-force of the generator and on the resistance of the circuit.

The fact that the torque of a series motor depends only on the current is of advantage in the application of motors to propulsion of vehicles (such as tram-cars) which at starting require for a few seconds a power greatly in excess of that needed when running.[1] To start, a large current must be turned on. One convenient way of arranging this is to use two motors, coupled habitually in series. When starting, they are, by moving a commutator, coupled in parallel. This doubles the electromotive-force for each, and at the same time halves the resistance. For a few seconds a very strong current flows—much stronger than that which the motors would stand for any prolonged work—and so provides the needful additional torque.

In the series motor, when supplied at constant potential, E is not proportional to the speed, because the field-magnetism is not constant, but falls off as E increases, being (if unsaturated) nearly proportional to $\mathcal{E} - E$. It therefore will not run at a constant speed. Neither will it run at a constant speed if supplied with a constant current.

Use of two Series Motors in Transmission.—It is known that if two similarly-constructed series-wound machines are used—one as generator, the other as motor—the arrangement is almost perfectly self-regulating, the speed of the motor at the receiving end being almost constant if that of the dynamo at the transmitting end is constant. Every addition to the load put upon the motor, tending to check the speed, causes an increase of current to flow, and so throws a proportionate additional work upon the generator, which in turn takes more power from the steam-engine to keep up its speed. As we have shown above, the torque of the motor T_2 will depend, in the given machine, on the current alone, and on the current will depend the torque at the dynamo T_1. Mr. Kapp has further shown[1] how, if there is a resistance in the line, the arrangement may still be made self-regulating by choosing as generator and motor two machines so wound that, comparing their characteristics for the prescribed speeds, the difference in their electromotive-forces corresponding to a given value of current shall be equal to the electromotive-force requisite to drive that particular current through the resistance in the whole circuit. Some further particulars of series machines are given in Chapter XXVI., on Transmission of Power.

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[1] See remarks by E. Hopkinson, *Proc. Inst. Civil Engineers*, xci. pt. i. 6, 1887.

The late Sir C. W. Siemens[2] drew attention in 1880 to the singular properties of the combination of a generating dynamo and a magneto motor, instancing a locomotive motor which, when descending an incline, quickens its speed and actually becomes a generator of currents, paying back the spare power into store. He also remarked how two trains driven by motors running on the same pair of electric rails, tend to regulate one another, the one on a descending portion of the road transmitting power to the other, as though "connected by means of an invisible rope."

SHUNT MOTOR.

The fundamental conditions are as follows:—

$$T = i_a \frac{C N}{2 \pi};$$

$$i_a = i - i_s;$$

---

[1] See Kapp's *Electric Transmission of Energy*, p. 176.

[2] *Journal Soc. Telegr. Engineers*, ix. 301, 1880.

and, adopting the appropriate form for the law of magnetization from p. 167,

$$\mathrm{N} = \overline{\mathrm{N}}\,\frac{\mathcal{E}}{\mathcal{E} + \mathcal{E}'};$$

$$\mathrm{E} = \mathcal{E}\left(1 + \frac{r_a}{r_s}\right) - r_a i.$$

From the first three of these we get

$$\mathrm{T} = \frac{\mathrm{C}}{2\pi}\left(i - \frac{\mathcal{E}}{r_s}\right)\overline{\mathrm{N}}\,\frac{\mathcal{E}}{\mathcal{E} + \mathcal{E}'};$$

and, transposing and writing Y for $\mathrm{C}\,\overline{\mathrm{N}} \div 2\pi$,

$$i = \frac{\mathrm{T}}{\mathrm{Y}} \cdot \frac{\mathcal{E} + \mathcal{E}'}{\mathcal{E}} + \frac{\mathcal{E}}{r};$$

and from the last of the four

$$n = \frac{1}{\mathrm{C}\,\mathrm{N}}\left\{\mathcal{E}\left(1 + \frac{r_a}{r_s}\right) - r_a i\right\}.$$

Inserting the value of i, we have

$$n = \frac{\mathcal{E} + \mathcal{E}'}{2\pi \mathrm{Y}}\left\{1 + 2\frac{r_a}{r_s} - \frac{r_a \mathrm{T}}{\mathrm{Y}} \cdot \frac{\mathcal{E} + \mathcal{E}'}{\mathcal{E}^2}\right\}.$$

Case (i.): $\mathcal{E}$ *constant.*

The last equation shows that a shunt-motor, supplied at constant potential, will have a speed that would be constant and independent of the torque if it were not for internal resistance ; and further, that the consequent falling off as the torque increases will be the less as the field-magnetism is the more powerful.

As an example, a Victoria shunt motor tested by Mr. Mordey, in which the load was varied from $91{\cdot}8 \times 10^7$ to $1357{\cdot}2 \times 10^7$ dyne-centimetres, only decreased its speed from 16·25 to 15·75 revolutions per second.

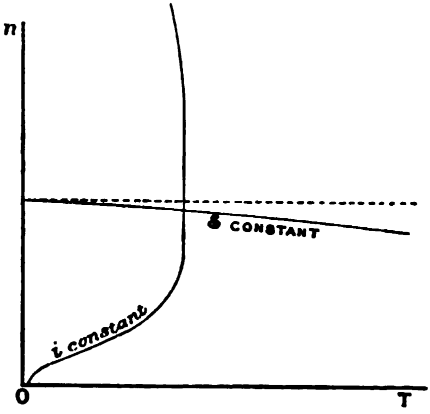
It is instructive to contrast the self-regulating power of a shunt dynamo with the self-governing power of a shunt motor. The former, when driven at a constant speed, generates electric power at a nearly constant potential ; the latter, when supplied from the mains at a constant potential, would furnish mechanical power at a nearly constant speed; and in both cases the departure from absolute constancy is proportional to the internal resistance of the armature coils, and to the output, electrical or mechanical, of the machine for the time being.

So far we have supposed the armature to exert no magnetic reaction. Now, as we shall see, to obtain sparkless running there must be a backward lead, and in motors a backward lead tends to demagnetize. But demagnetizing tends, as we have seen, to increase the speed; hence in the case of constant-pressure supply, when there is a great load, the very reaction of the great current will tend to prevent the speed from falling, making the shunt motor very nearly self-regulating. These reactions must now be considered in detail.

Case (ii.): *i constant.*

The determination of this case is more complicated, though the general considerations are simple enough. If the motor is standing still when the current is turned on, nearly all the current will go through the armature, next to none through the shunt; hence there will be little magnetism, and therefore

FIG. 381.



MECHANICAL CHARACTERISTICS OF SHUNT MOTOR.

almost no torque. Such a machine will not start itself with any load on; but if it be once started, its counter electromotive-force will cause the current in the armature to decrease, whilst that round the shunt increases. The torque will therefore then increase with the speed, but not indefinitely, for as the magnetism advances in its degree of saturation, the increase of N will no longer compensate for the decrease of i_a; and from that point onwards the torque will decrease if the speed is allowed to increase. And, hypothetically, the speed should increase until the motor's own electromotive-force exactly equals the difference of potentials due to the whole of the constant current flowing through the resistance of the shunt, under which circumstances there will be no current through the armature and zero torque. Fig. 381, which, like the preceding, is taken from Dr. Frölich's work, gives the mechanical characteristics for the two cases.

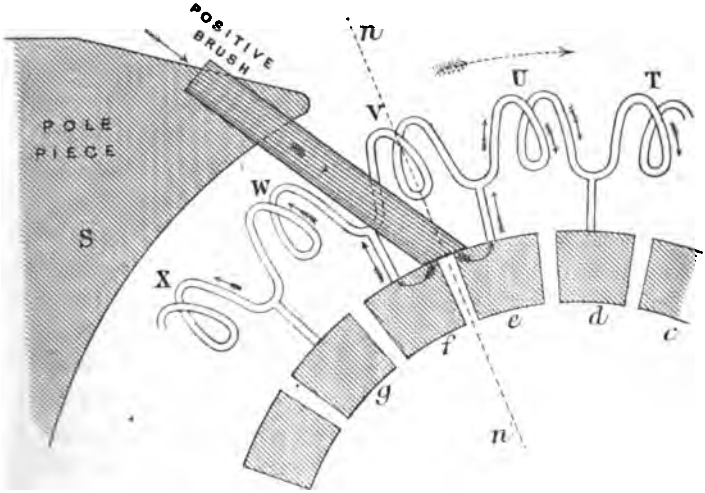
REACTION BETWEEN ARMATURE AND FIELD-MAGNETS IN A MOTOR.

In Chapter IV., pp. 62 to 103, the reactions between the armature and field-magnets of a dynamo were considered in detail, but attention was confined solely to that which occurs when the dynamo is used as a generator. In that case the current induced in the armature coils tended to magnetize the armature core in a direction nearly at right angles to the direction in which the field-magnets magnetized it, and in consequence there was a resultant magnetization at an oblique angle. This obliquity compelled a certain angular lead to be given to the brushes in the sense of the rotation; and the necessary result of the forward lead of the brushes was to cause the armature current to tend partially to demagnetize the field-magnets. Reference to Fig. 59, p. 76, will show that wherever the brushes are placed there is a tendency to form corresponding poles, and these armature poles tend to produce in the iron pole-pieces of the field-magnets an opposite polarity to their own, and therefore to weaken or strengthen the field according to the lead. The same thing is true of a motor; but with a difference. A current supplied from an external source magnetizes the armature and makes it into a powerful magnet, whose poles would lie, as in the dynamo, nearly at right angles to the line joining the pole-pieces, were it not for the fact that in this case also a lead has to be given to the brushes. Suppose, as in most of the drawings in this book, that the S pole of the field-magnets is on the left, and the N pole on the right. Also that the current so traversed the armature that it caused the highest point to be a S pole and the lowest point a N pole. This means that if the armature is wound right-handedly the current must come in through the top brush and leave by the bottom one, the top brush being connected to the + main. Compare with p. 64. Clearly, in this case, the armature will rotate right-handedly, because the S pole at the top will be repelled from the S pole on the left and attracted toward the N pole on the right. It will therefore run right-handedly (in a right-hand field) when the current flows downwards from top to bottom, exactly as the armature of a generator must run in order to send a current upwards. In each case the direction of the induced electromotive-force is the same—upwards—*with* the current in the dynamo, *against* the current in the motor.

It follows that a forward lead would convert the cross magnetizing-force into one that tends to increase that of the field-magnet, whilst a backward lead tends to demagnetize. Further, since with a forward lead the armature polarity strengthens that of the field-magnet, it is possible for a motor to be worked without any other means being taken to magnetize the field-magnets, the armature will induce a pole in the field-magnet and then attract itself round towards this induced pole. This principle has been used for many years in small motors, having been apparently first applied by Wheatstone.

The cross-magnetizing force will also have the effect of weakening the field under the two leading pole-tips, and of strengthening them under the two trailing pole-tips. This is the opposite effect to that in a dynamo. In the motor (without lead even) the cross-magnetizing reaction tends to shift round the field in a sense *opposite* to that of the rotation. We shall now see what are the conditions for minimum sparking. Consider (Fig. 382) a coil W ascending on the left. The current in it is descending from the top brush, whilst it is itself the seat of an electromotive force that tends to stop or reverse its current. Now we know that the condition of non-sparking requires that at the moment whilst the coil passes under the brush, and is short-circuited, it should be passing through a field that is not only sufficiently strong, but one that tends to reverse the direction of its current. It is already in such a field; hence the act of commutation must take place *before* it passes out of this magnetic field. It must be commuted before it arrives at the highest point. In other words, a backward displacement must be given to the brushes if there is to be no sparking. The neutral line *n n'* will therefore rake *backwards* in a motor into the fringe of the magnetic

FIG. 382.



THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A MOTOR.

field. But since (in every case) both eddy-currents and hysteresis tend to shift the magnetic field slightly in the direction of the rotation—increasing the lead in a generator, diminishing it in a motor—it follows that the negative (or backward) lead in a motor may be slightly less than the positive (or forward) lead in a generator, for equal flow of current and equal excitation.[1] The advantage in point of weight of a motor in which the armature should help to excite the field-magnets, thereby reducing the power and weight of the latter, led Professors Ayrton and Perry,[2] in 1883, to advocate designs with weak field-magnets and powerful armatures acting with a forward lead. But from the foregoing considerations it follows that if a forward lead is given to the brushes of a motor in order to get a more powerful rotation, the motor will inevitably spark at the brushes. The fascinating notion of using the armature to magnetize has proved a failure in practice. With a forward lead the motive power relatively to weight would be undoubtedly larger than with a backward lead, but it is accompanied by destructive sparking. Minimum of sparking may be reconciled with high efficiency, but only by one way. That way is to design and construct motors so that the armature shall not perturb the magnetic field due to the field-magnets. This can be accomplished by following out the very same principles of design and construction which were found to be correct guides in the case of dynamos used as generators. *The field-magnets must be made very powerful in proportion to the armature.* If they are, then there will be no perturbations, no obliquity in the resultant magnetic field, no lead to the brushes, and no sparking. Only in the few cases when minimum weight is of more importance than high efficiency, can this rule be departed from, and then it becomes necessary to take special means, such as providing auxiliary poles, or specially shaped pole-pieces, to prevent the sparking which would follow from having small or weak field-magnets.

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[1] This appears to be the explanation of the differences—otherwise unimportant—observed by Snell; *Journal Inst. Electr. Engineers*, xix. 194, 1890.

[2] *Journal Soc. Telegr. Engineers*, xii. May 1883.

Mr. Mordey,[1] who has carefully tracked out the analogies between dynamos and motors, has observed that in several respects it is even more important that the rules laid down for the good design of generators should be observed for motors. Eddy-currents must be even more carefully eliminated. Also the greatest attention must be paid to proper mechanical arrangements for transmitting to the shaft the forces that are thrown by the magnetic field upon the conducting wires around. See Chapter XIII.

Consider the conditions which are bound up in the disposition of the magnetic fields of the generator and the motor respectively. In one the armature is mechanically driven round while the magnetic forces in the field tend to pull it back. In the other, the magnetic forces of the field tend to drag it round, and it is thereby enabled to do mechanical work. In one case there is an opposing mechanical reaction tending to stop the steam-engine. In the other there is set up an opposing electrical reaction (the induced counter electromotive-force) tending to stop the current.[2] In both cases the rotation is supposed to be taking place in the same sense—right-handedly. In both the effect is to displace the lines of force of the field, but in the generator the mechanical rotation acts as if it dragged the magnetism round, whilst in the motor the reciprocal magnetic reactions act as if they tried to drag round the armature, producing mechanical rotation. In the generator we found that the effect of self-induction in the armature was to require a positive lead. In the motor, on the contrary, the effect of self-induction is to necessitate a negative lead. If a motor is set with no lead, and if the field-magnets are very weak or are not excited at all, it will run in either direction according as it may be started.

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[1] *Phil. Mag.*, Jan. 1886.

[2] The law of the electrical reaction resulting in a generator from the mechanical motion is summed up in the well-known law of Lenz, that *the induced current is always such that by virtue of its electro-magnetic effect it tends to stop the motion that generated it.* In the converse case of the mechanical reaction resulting, in a motor, from the flow of electric energy, it is easy to formulate a converse law, viz. that *the motion produced is always such that by virtue of the magneto-electric inductions which it sets up it tends to stop the current.*

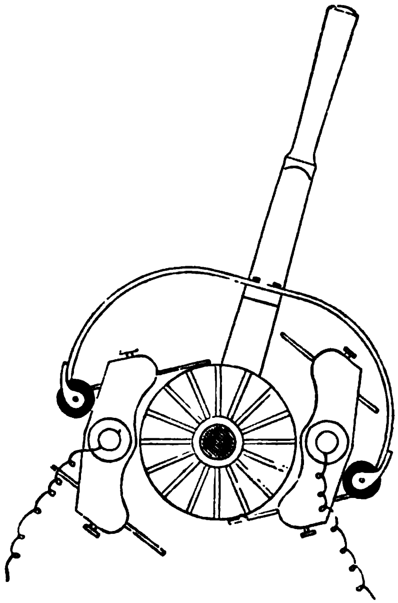
If in a motor with well-excited field-magnet the current be reversed in the *armature part* of the circuit only, the motor will usually reverse its rotation, but will usually require the lead to be reversed to run as sparklessly as before. If, instead of reversing the current in the armature, the magnetism of the field-magnet be reversed, a similar result will follow. If both are reversed at the same time, the motor will go on rotating as if nothing had happened.

Dynamos wound and connected for working as generators of continuous currents may be used in all cases as motors, but with some difference. A series dynamo set to generate currents when run right-handedly (and therefore having a forward right-handed lead), will, when supplied with a current from an external source, run as a motor, but runs left-handedly against its brushes. To set it right for motor purposes requires *either* that the connexions of the armature should be reversed, *or* that those of the field-magnet should be reversed (in either of which cases it will run right-handedly), *or* else the brushes must be reversed and given a lead in the other direction (in which case it will run left-handedly). A shunt dynamo set ready to work as a generator will, when supplied with current, run as a motor in the same direction as it ran as a generator; for if the current in the armature part is in the same direction as before, that in the shunt is reversed, and *vice versâ*. A compound-wound dynamo, set right to run as a generator will run as a motor in the reverse sense, against its brushes if the series part be more powerful than the shunt, and with its brushes if the shunt part be the more powerful. If the connexions are such (as in compound dynamos) that the field-magnet receives the sum of the effects of the shunt and series windings when used as a generator, then it will receive the difference between them when used as a motor. There are certain advantages in using a differentially-wound motor, as will appear hereafter.

The subject of alternate-current machines as motors is treated separately in Chapter XXIV.

REVERSING GEAR FOR MOTORS.—A motor, as will be seen from the preceding discussion, can be reversed by the operation of reversing the current through the armature, and at the same moment reversing the lead. But reversing the current can also be accomplished by rotating the brushes through 180°. Consequently both, these actions may be accomplished by the single operation of advancing the brushes through $180° - 2\phi$, where ϕ is the original angle of lead. But as the brush would then slant in the wrong direction, it is better to provide a second set of brushes. This is, indeed, Hopkinson's method of reversing. He employs two pairs of brushes, each pair being capable of moving about a common pivot, so that either the pair having a lead in one direction, or the pair having a lead in the other direction can be let down upon the collector. A reversing gear, designed by Mr. A. Reckenzaun for the motors of the launch *Electricity*, is shown in Fig. 383. In it there are two pairs of brushes; the two upper are fixed to a common brush-holder, which turns on a pivot, and can be tilted by pressing a lever handle to right or to left. The two lower brushes are also fixed to a holder. Against each brush-holder presses a little ebonite roller, at the end of a bent steel spring, fixed at its middle to the handle.

FIG. 383.



REVERSING GEAR FOR ELECTRIC MOTOR.

The result of this arrangement is that, by moving the lever, the brushes can be made to give a lead in either direction, and so starting the motor rotating in either direction. Such a reversing gear is obviously a most useful adjunct for industrial applications of motors, and if the difficulties of sparking at the brushes caused by the sudden removals of them from the collector be obviated, must prove much better than any mechanical device to reverse the motion by transferring it from the axle of the motor through a train of gearing to some other axle. One great advantage of electric motors is, that they can be easily fixed directly on the spindle of the machine which they are to drive; an advantage not lightly to be thrown away.

Another form of reversing gear has been designed by Professors Ayrton and Perry. It consists of a double collar upon the spindle of the motor; in one, the inner collar, having a pin fitting into a spiral groove in the spindle, and being free to move relatively to the spindle. Any displacement along the spindle given to the inner collar through the outer one causes the pin in the former to move along the groove, and the collar rotates through a certain angle. This collar, in Ayrton and Perry's motor, carries the brush-holders, and therefore by rotating alters the lead. Motors fitted with this gear were depicted in earlier editions of this work. Other forms of reversing gear for small motors have been designed by the author, who cuts the segments of the collector or commutator spirally, and therefore obtains a change of lead by simply sliding the brushes forward or backward parallel to the axle of the motor.

In Reckenzaun's motor the reversing gear consists of two pairs of brushes which are mounted so as to slide on guides or ways; reversal being accomplished by shifting a lever which slides forward one pair whilst it draws the other pair back.

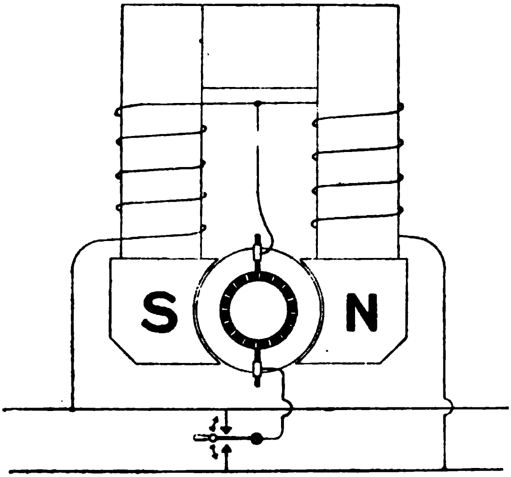
It is also theoretically possible to construct a motor which shall reverse by simply reversing the current in the armature part; for this end the pole-pieces must be so shaped that when no angular lead is given to the brushes, the angle between the diameter of commutation and the effective pole in the pole-piece shall be that required for steady running. If this can be found, then merely reversing the polarity of either part will reverse the motor.

If the field-magnets of a motor are so powerful relatively to the armature that no lead has to be given to the brushes, the rotation can be reversed by reversing the polarity of either part. In Immisch's larger motors, the reversing-gear, which is very substantial, removes one pair of brushes and puts down at the same diametral points a second pair, reversed in position and polarity.

The form of brush shown in Fig. 276 *c*, p. 381, is designed by Holroyd Smith for motor work, as it allows of rotation in either direction. So also do carbon-brushes, such as Fig. 277, p. 382.

Another mode of reversing was suggested by the author[1] in 1882. It is indicated in Fig. 384. It consists in joining one of the brushes to a point half-way along the field-magnet coils, which, though connected across the mains as a shunt, must not be of very high resistance. The current in the armature can then be reversed by simply switching the second brush from one main to the other. This principle is used in Maquaire's regulator (Fig. 486).

FIG. 384.



ELECTRIC REVERSING GEAR FOR A MOTOR.

GOVERNMENT OF MOTORS.

It is extremely important that electric motors should be so arranged as to run at a uniform speed, no matter what their load may be. For example, in driving lathes, and many other kinds of machinery, it is essential that the speed should be regular, and that the motor should not "race" as soon as the stress of the cutting tool is removed.

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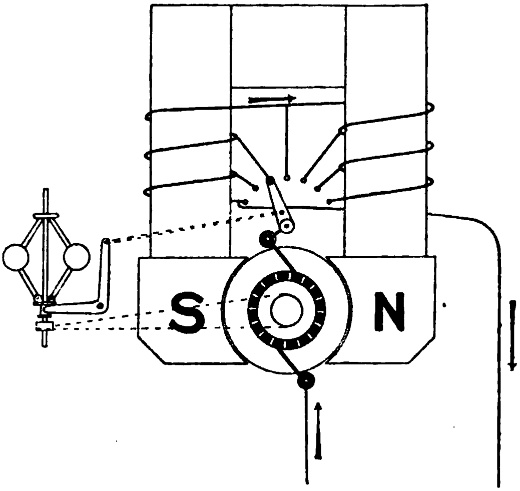
[1] Specification of Patent, No. 5122 of 1882.

Interruptor Governor. — One of the earliest attempts to secure an automatic regulation of the speed was that of M. Marcel Deprez, who in 1878 applied an ingenious method of interrupting the current at a perfectly regular rate by introducing a vibrating brake into the circuit. The motor employed had a simple 2-part commutator, whose rotation timed itself to the makes-and-breaks of the current. This method is, however, inapplicable to large motors.

CENTRIFUGAL GOVERNING.

Spasmodic Governor. — Another suggestion, equally impracticable on the large scale, was to adopt a centrifugal governor to open the circuit whenever the motor exceeded a certain speed. A motor so governed runs spasmodically fast and slow.

FIG. 385.



AUTOMATIC CENTRIFUGAL GOVERNOR.

It is also possible for a centrifugal governor to be employed to vary the resistance of a part of the circuit; for example, to work an automatic adjustment to shunt part of the current of a series machine from its field-magnets, or to introduce additional resistance into the field-magnet coils of a shunt-wound machine, in proportion to the speed. A case is shown in Fig. 385, in which a centrifugal governor driven by the motor alters the number of exciting coils in the field-magnet circuit, causing the magnetism to increase if the motor runs too fast, and so brings down the speed again. This method was proposed by Brush, and answers well for motors in arc-light circuits.

Periodic Governor.—Professors Ayrton and Perry have also proposed several forms of "periodic" centrifugal governor, a device by which in every revolution power is supplied during a portion of the revolution only, the proportion of the time in every revolution during which the power is supplied being made to vary according to the speed. The main difficulty with such governors is to prevent sparking. But there is a still more radical defect in all centrifugal governors: they all work too late. They do not perform their functions until the speed has changed. The perfect governor will not wait for the speed to change.

DYNAMOMETRIC GOVERNING.

The author devised[1] another kind of governor which is not open to this objection. He proposed to employ a dynamometer on the shaft of the motor to actuate a regulating apparatus, consisting, either of a periodic regulator to shunt or interrupt the current during a portion of each revolution, or of an adjustable resistance connected in part of the circuit. The dynamometric part may take the form of a belt dynamometer (such as Alteneck's) or of a pulley dynamometer (such as Morin's or Smith's). In the latter case, which is the more convenient, a loose pulley runs on the motor shaft and is connected by a spring arrangement with a fixed pulley. The rotation of the motor will drag round the fixed pulley in advance of the loose pulley, and the angular advance will be proportional to the turning moment or torque. The amount of such angular advance determines the action of the regulating part. The regulator in this case is therefore worked, not according to the speed of the motor, but according to the load it is carrying. Any change in the load will instantly act on the dynamometric governor before the speed has time to change. If such a governor is purposely over-set it may even have the effect of causing the motor to run faster when the load comes on than it does when running idle.

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[1] Specification of Patent, No. 1639 of 1883.

ELECTRIC GOVERNING.

Another method of governing, not requiring any rotating parts, has been proposed by the author. He uses as field-magnets a double set of poles, set at different angles with respect to the brushes of the motor. One pair of magnetic poles, having a certain lead, is actuated by series coils, the other pair, having a different lead, by shunt coils. When both shunt and series are working, there will, of course, be a resultant pole having some intermediate lead. If the load of the motor is diminished it will tend to run faster, increasing the current in the shunt part, decreasing it in the series part, and therefore altering the effective lead and preventing the increase of speed.

In 1880 a motor was patented by Mr. G. G. André in which the field-magnets were wound in two separate circuits, one of thick and the other with thin wire, the current dividing between them, and the armature was connected as a bridge across these circuits exactly as the galvanometer is connected across the circuits of a Wheatstone's bridge. Motors governed on this principle have been constructed, since 1884 onwards, by Lieut. F. J. Sprague; they showed remarkably good regulation.

The method of automatic regulation that is most perfect in theory is undoubtedly that imagined by Professors Ayrton and Perry, and expounded in their paper in the *Journal of the Society of Telegraph Engineers.*[1] The theory of self-regulation propounded by them demands the most careful attention. It is expounded in the following pages; but the symbols employed have the same meaning as in the chapters which precede. Professors Ayrton and Perry originally employed an argument in which one part of the motor is regarded as acting as a brake to another part. The author prefers to regard the use of a shunt winding with an opposing series winding—which is the final result of this method of regulation—as simply a differential winding designed to produce a certain result.

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[1] Vol. xii. May, 1883; see also a later paper in *Phil. Mag.*, 1888.

THEORY OF SELF-GOVERNING MOTORS.

In the section on Self-regulating Dynamos, on pp. 277 to 294, were set forth the methods of solving the problem how to arrange a dynamo so that it shall feed the circuit with electric energy under the condition of a constant potential, when driven at a constant speed. The solution to that problem consisted in the employment of certain combinations for the field-magnets which gave an initial magnetic field independent of the current that might be flowing in the main circuit.

Now it is not hard to see that this problem may be applied conversely, and that motors may be built with a combination of arrangements for their field-magnets, such that, when supplied with currents under the standard condition of constant potential in the distributing mains, their speed shall be constant whatever the load. It will be evident without any numerical calculations that the windings must oppose one another—one must tend to demagnetize the field magnet, the other to magnetize: Take the case of a shunt motor supplied at a constant potential $\mathcal{E}$, and running at a certain speed with a certain load. If the load is suddenly removed the motor will begin to race, its racing will increase the counter electromotive-force developed and will partly cut down the armature current. But the decrease of current will not be quite adequate to bring back the speed, because of the internal resistance of the armature, which has prevented the whole energy of the armature current from being utilized as work. A demagnetizing series coil of appropriate power wound on the field-magnet will, however, effect what is wanted, for then, with any reduction of load, the corresponding reduction of current can take place, the resulting increase in the field-magnetism being sufficient to get the required larger counter electromotive-force without any increase in speed. The combination may, therefore, rightly be regarded as a differential winding. For constant-current distribution no method of compound winding, whether differential or additive, has been found satisfactory; and special regulators are employed.

The following synoptical table contrasts the arrangements for self-regulating generators with those of self-governed motors :—

GENERATOR.	MOTOR.
Given Constant Speed.	*To get Constant Speed.*
To get *e constant.*	Given $\mathcal{E}$ *constant.*
Initial magnetism { Steel magnets. Separate excitation. Shunt coils.	Initial magnetism { Steel magnets. Separate excitation. Shunt coils.
+ Series-regulating coils.	— Series-regulating coils.

In discussing the theory of the self-governed motor, we shall follow the same general lines as in discussing the theory of the self-regulating generator, namely, find an equation expressing the desired condition of constancy.

Case (i.)—*Given : $\mathcal{E}$ constant.*

(*a*) *Magneto Motor with Series-regulating Coil.*—Using the same notation as previously, we have for the counter electromotive-force developed in the armature—

$$E = n \, C \, N ;$$

also

$$E = \mathcal{E} - (r_a + r) \, i.$$

Now N is made up of two parts, viz. :—N_1 the permanent part, and another part depending on the series coil which we may write $q\,S\,i$; where q has the same signification as on p. 283, and is equal to 4π divided by ten times the sum of the magnetic reluctances. Its value therefore depends upon the permeability, and therefore upon the degree of saturation of the iron of the magnetic circuit. Reserving this point for further consideration, we may write

$$\mathrm{N} = \mathrm{N}_1 - q\,\mathrm{S}\,i.$$

If we had written + instead of −, we should find the solution coming out with the negative sign, indicating that the windings must be so arranged that the current in the series coil circulates in the negative or demagnetizing sense. We write the negative sign, however, as we already know that this must be so. We also assume at present that there are no armature reactions. Substituting the value of N in the fundamental equation, we have

$$\mathrm{E} = n\,(\mathrm{C}\,\mathrm{N}_1 - \mathrm{C}\,q\,\mathrm{S}\,i);$$

and equating this to the other value of E in the second equation above, we find

$$n = \frac{\mathcal{E} - (r_a + r_m)\,i}{\mathrm{C}\,\mathrm{N}_1 - \mathrm{C}\,q\,\mathrm{S}\,i}. \qquad \text{[I.]}$$

Having thus obtained an expression for the speed, we must examine the various parts of the expression to see which are variable and which constant, and so deduce a relation which shall make n constant. Now in both numerator and denominator there are two terms, the first of which is a constant, whilst the second of each contains the variable i. A little consideration will show that the fraction cannot have a constant value unless the two coefficients of the variable in the second terms bear the same ratio to one another as do the two constants which stand as the first terms; or n cannot be constant unless

$$\frac{\mathcal{E}}{\mathrm{C}\,\mathrm{N}_1} = \frac{r_a + r_m}{\mathrm{C}\,q\,\mathrm{S}},$$

or

$$\frac{\mathcal{E}}{\mathrm{N}_1} = \frac{r_a + r_m}{q\,\mathrm{S}}, \qquad \text{[II.]}$$

which is the desired equation of condition.

If this condition be observed (and it will be noted that the quantity of series winding required is proportional, as in the self-regulating dynamo, to the internal resistance of the machine), then the speed will be constant and of the value

$$n = \frac{\mathcal{E}}{\mathrm{C}\,\mathrm{N}_1} = \frac{r_a + r_m}{\mathrm{C}\,q\,\mathrm{S}}. \qquad \text{[III.]}$$

From the first of these relations we see that the speed at which the machine is thus governed to run is the same speed as that at which, if driven as a generator on open circuit, it will yield an electromotive-force equal to that of the supply at the mains. When running as an unloaded motor, it ought of course to turn so fast as to reduce the current through its armature to a minimum, which it can do by running at this speed. It is evident that by making the permanent part of the magnetism strong enough, the critical speed—that is to say, the speed for which the motor is self-governing—may be made as low as desired. As the load on the motor is increased, the flow of current through the armature must be increased, and this increased current cannot flow unless in some way the counter electromotive-force of the armature be diminished. As the speed is to be kept up, this is accomplished by the lowering of the magnetism, which occurs in consequence of the increased current flowing through the demagnetizing coils. The quantity denoted by q, which depends on the permeability of the iron, ought of course to be taken at an average value between the two extremes which it has at maximum load and at zero load. The magnetism is a maximum when the motor is running empty. When the load is greatest, if the motor is running at, say, 80 per cent. efficiency, E will be 80 per cent. of $\mathcal{E}$; that is to say, N will be 80 per cent. of N_1. It is between these limits in the magnetization that the value of q must be averaged. It is evident from equation [III.] that if the motor is already provided with a given series winding, there can be found a value of $\mathcal{E}$, for which the condition of self-governing can be still fulfilled. All the preceding argument applies also to separately-excited motors.

(*b*) *Shunt Motor with Series-regulating Coil.*—This really includes two cases: namely, shunt and long-shunt. We take the latter case, which is the usual one. The fundamental equations will now be

$$
\begin{aligned}
\mathrm{E} &= n\,\mathrm{C}\,\mathrm{N}, \\
\mathrm{E} &= \mathcal{E} - (r_a + r_m)\, i_a, \\
\mathcal{E} &= r_s\, i_s, \\
\mathrm{N} &= q\,\mathrm{Z}\, i_s - q\,\mathrm{S}\, i_a,
\end{aligned}
$$

From these we get successively

$$n = \frac{\mathrm{E}}{\mathrm{C}q\mathrm{Z}i_s - \mathrm{C}q\mathrm{S}i_a},$$

$$n = \frac{\mathcal{E} - (r_a + r_m)\, i_a}{\mathrm{C}q\mathrm{Z}i_s - \mathrm{C}q\mathrm{S}i_a},$$

$$n = \frac{r_s i_s - (r_a + r_m)\, i_a}{\mathrm{C}q\mathrm{Z}i_s - \mathrm{C}q\mathrm{S}i_a},$$

which cannot be constant unless the respective coefficients of i_s and i_a in the numerator bear the same ratio to one another as do the corresponding ones in the denominator, giving as the equation of condition

$$\frac{r_s}{\mathrm{C}q_1\mathrm{Z}} = \frac{r_a + r_m}{\mathrm{C}q_2\mathrm{S}},$$

The values of q are here distinguished by suffixes for the following reason :—If the above relation is fulfilled, then when the motor runs with zero load there will be practically no current through the armature, and the counter electromotive-force $n\,\mathrm{C}\,q_1\,\mathrm{Z}\,i_s$ will be equal to $\mathcal{E}$. At this stage of things, when the shunt coil is in full work, the magnetism is at its maximum, and q_1 (which is proportional inversely to the total magnetic resistance) will be at its minimum value. On the other hand, when the motor is driving its maximum load, the armature current (and therefore the demagnetizing effect of the regulating coils) is at its maximum, the magnetization will be at its lowest running value, and q_2 will be at its maximum. This being premised, the equation of condition may be written

$$\frac{Z}{S} = \frac{r_s}{r_a + r_m} \cdot \frac{q_2}{q_1}. \qquad \text{[IV. (a).]}$$

In the earlier editions of this work saturation was left out of account, and the formulæ were only approximate, the equation having the form

$$\frac{Z}{S} = \frac{r_s}{r_a + r_m}, \qquad \text{[IV.]}$$

which is Ayrton and Perry's rule for the winding of the self-governing motor. It may be remarked, however, since in a well-designed motor the resistances in the armature-circuit are very small, and the efficiency as a whole high, the demagnetizing effect of the series coils, even at full load, need only reduce the magnetization by a small percentage, so that q_2 may be nearly equal to q_1. Moreover, if a backward lead be given to the brushes, the armature itself may act partially as a demagnetizing series coil, and so compensate for alteration in the permeability. It is quite certain that motors wound differentially in the proportion indicated in equation [IV.] are very nearly self-governed. Some excellent motors by Lieut. F. J. Sprague are wound according to this rule. One very curious property of this method of winding is as follows: —Suppose the motor to be standing still and the current turned on, the ampere-turns due to the shunt will be equal to $\mathcal{C}\,Z \div r_s$, whilst those due to the series coil will be $\mathcal{C}\,S \div r_a + r_m$; and these, according to equation [IV.], will be equal, and they are of opposite sign. There should then be no magnetism excited at all. But if there is any lead at the brushes, the magnetizing tendency of the armature will come into play; and if the brushes have a considerable negative lead, the effect will be to magnetize the field-magnet in the wrong sense, and then the motor starts the wrong way. The defect might be remedied by cutting out the series coil or reversing it, until the motor has got up its speed. The latter course is preferable, as the additional torque of the series motor is of great advantage in overcoming the statical resistance to motion experienced at starting.

It is obvious that the number of shunt-turns should theoretically be such that the motor, driven on open circuit at the given speed, shall generate an electromotive-force equal to $\mathcal{E}$.

Practical Determination of the Shunt and Series Windings.[1]—As in the case of compound winding of dynamos (p. 292) so for motors, the proper windings can be found by simple experiments, a temporary coil being wound and separately excited, and a resistance equal to the future r_m being added to the armature resistance. Two experiments are required. Run the motor first with no load at the brake, using the proper potential $\mathcal{E}$, and excite the temporary coil, observing the number of ampere-turns that are needful to bring the speed down to the required n. The number of ampere-turns in this case is equal to $Z\, i_s$, where i_s is the current, which economy dictates should be used in the shunt. Secondly, run the motor with its fullest load at the brake, and again excite the field-magnet with such a number of ampere-turns that the speed is constant at n. From this and the previous experiment S can be calculated.

The efficiency of a differentially-wound motor cannot be expected to be as high as that of one which is non-differentially wound, since the energy expended in the former case in magnetizing the field-magnets is greater relatively to the amount of magnetization produced. Thus, if the demagnetizing coil has a value in ampere-turns of one-fourth of the magnetizing coils, the energy required to give the necessary magnetization will be 50 per cent., or half as much again as in the case of simple direct magnetization.[2]

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[1] It should be pointed out that this process differs from that suggested by Professors Ayrton and Perry in their paper on electromotors, in *Journal Soc. Teleg. Engineers*, May 1883. Their method depends on the volume left on the bobbins of the field-magnets, which is assumed to be constant.

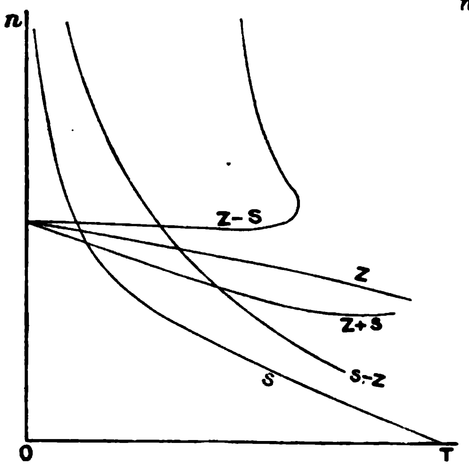
[2] Some elaborate observations upon compound-wound motors, when worked with constant potentials and constant currents, have been published by Dr. Frölich in the *Elektrotechnische Zeitschrift* for June 1885.

MECHANICAL CHARACTERISTICS OF COMPOUND DIFFERENTIAL MOTORS.

It may be convenient here to consider the graphic representation of the regulations between speed and torque in motors provided with mixed windings.[1]

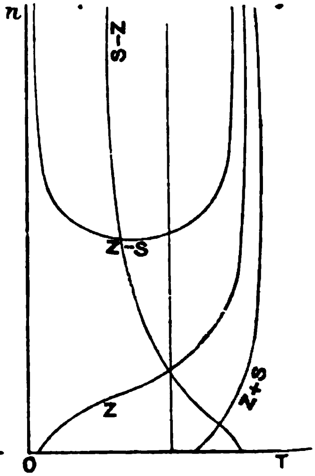
The curves for constant-potential supply are shown in Fig. 386, wherein the letters S and Z refer to series windings and shunt windings respectively. The forms of the curves for mixed windings differ somewhat according to the proportions of the two sets of coils. The important case is that of the differential winding marked Z — S, having a few series turns to correct the droop of the pure shunt-winding, and it will be noted that up to a certain limit the speed is nearly constant, but that there is a maximum value to the torque. In the

FIG. 386.



MECHANICAL CHARACTERISTICS AT CONSTANT POTENTIAL.

FIG. 387.



MECHANICAL CHARACTERISTICS WITH CONSTANT CURRENT.

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[1] The author is indebted to Frölich's *Die Dynamoelektrische Maschine* for the curves of motors with mixed windings. Similar curves have been deduced by Rechniewski, see *Séances de la Société de Physique*, 1885, p. 197.

case of constant-current supply, as the curves of Fig. 387 show, the only winding which gives any approximation to a constant speed is the differential winding with large shunt and small series coil. For, as in the case of the constant-current generator, the variation of the magnetism has to be carried through an enormous range, defying any averaging of the magnetic permeability.

An elegant graphic method of treating the problem of self-government of motors is given by M. Picou in *La Lumière Électrique*, xxiii. 114, 1887.

OTHER METHODS OF GOVERNING MOTORS.

A further suggestion for governing motors is due to Mr. Mordey and Mr. C. Watson. They wind the armature with two windings, having separate commutators. One winding—the main one—is the ordinary armature circuit of the motor, and is supplied with current from the external source, causing the armature to revolve. The other winding, which may be called the regulating armature-winding, is small in amount, and is disposed over, or side by side with, the main motor-winding. This additional winding is not connected to the mains or source of current, but to the field-winding by means of a special commutator or collector and brushes. It will be observed that this additional armature-winding, revolving in the field, constitutes a generator of current. The regulating action is as follows:—When a tendency to increase in speed results from a diminution of the load, the additional armature-winding tends to increase the strength of the field by supplying more current to the field-coils, and thus raises the opposing electromotive-force of the motor, diminishes the amount of current received from the mains, and so reduces the speed to its normal rate. Again, an increase of the load, tending to reduce the speed, is counteracted by a lessening of the magnetizing current produced by the additional winding, a consequent lowering of the opposing electromotive-force of the motor, and an increase of the current received from the mains. It will be seen that as this plan is summative it does not require so great an expenditure of energy in the fields as a differential winding; nor is it open to the objection that the motor may start in the wrong direction. On the other hand, it has the drawback of requiring an additional commutator. The method has given very good results, but has been rendered unnecessary, except in special cases, by the simpler plan to be next described. This is the important discovery by Mr. Mordey,[1] that if a pure shunt motor is constructed upon perfect designs—that is to say, having very small resistance of armature and very large resistance of shunt, and having also field-magnets, which are very powerful relatively to the armature, and an armature properly laminated and sectioned so as to reduce eddy-currents and self-induction to a minimum—such a shunt dynamo, if supplied from mains at a constant potential, will run at a constant speed whatever the load.[2] The slight demagnetizing action of the armature when a negative non-sparking lead is given to the brushes acts, in fact, instead of any special demagnetizing coil. The following tests showed a constancy to within 1½ per cent. for all loads within working limits.

Potential at Terminals.	Current (amperes).	Horse-power at Brake.	Revolutions per Minute.	Torque (pound-feet).
68·4	44	1·1	1125	5·15
68·4	126	7·4	1120	33·4
68·4	165·5	10·36	1115	48·8
68·4	180	11·14	1110	53·0

With a lower electromotive-force the same motor regulated almost equally well, but at a lower speed. It was observed that, especially when the motor was giving out small horse-power, that the speed was increased by weakening the field.

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[1] See *Phil. Mag.*, January 1886.

[2] This might have been foreseen from the equations of p. 602, in which if $r_a + r_m = 0$, the condition of regulation will give $S = 0$.

A possible mode of governing constant-current motors is by providing a variable magnetic shunt, in the converse of the manner suggested by Trotter for constant-current generators. Various other modes[1] of controlling the speed by altering the magnetism have been suggested, but few of them are automatic or reliable.

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[1] See a most interesting and fully illustrated paper by Mr. F. B. Crocker in *Electrical World*, xiii. 311, 1889.

CHAPTER XXI.

MODERN FORMS OF CONTINUOUS CURRENT MOTORS.

ALMOST any good modern dynamo (independently excited, shunt wound, or compound wound) will serve as a motor on mains supplied at the proper pressure; but attention has to be paid to the setting of the brushes that it may run rightly, and the machine so used must be one that will give the proper voltage at the proper speed. In designing motors precisely the same principles hold good[1] as obtain for designing generators; for the same features, namely, low internal resistance, powerful field-magnets, and proper elimination of eddy-currents, which go to make a good generator, also apply to the making of a good motor. For example: suppose it is desired to design a 10 HP. motor to run at 500 revolutions per minute, when fed at 200 volt mains. Now 10 HP. is 7460 watts; a motor to give out actually 7460 must be allowed to absorb (at 85 per cent. nett efficiency) 8776 watts. Further, if its electrical efficiency is to be, say, 90 per cent., it must generate 180 volts of counter electromotive-force. Dividing 8776 watts by 180 volts we find 48·75 amperes as the current it must take at normal load. If, therefore, we simply set to work to design a dynamo with good powerful field-magnets capable of generating 50 amperes at 180 volts at a speed of 500 revolutions per minute, we shall have obtained what we wanted.

Snell has given the following rules for expressing the actual HP. which may be safely and continuously taken from motors:—

Ring armatures, 2-pole; $\text{HP.} = 0{\cdot}00001 \times l d^2 n$,
Drum armatures, 2-pole; $\text{HP.} = 0{\cdot}000015 \times l d^2 n$;

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[1] For discussion of the subject of motor design, see a paper by Snell in *The Electrician*, xxii. 313 and 403, 1889; also *Journ. Inst. Electr. Engineers*, xx. 1891.

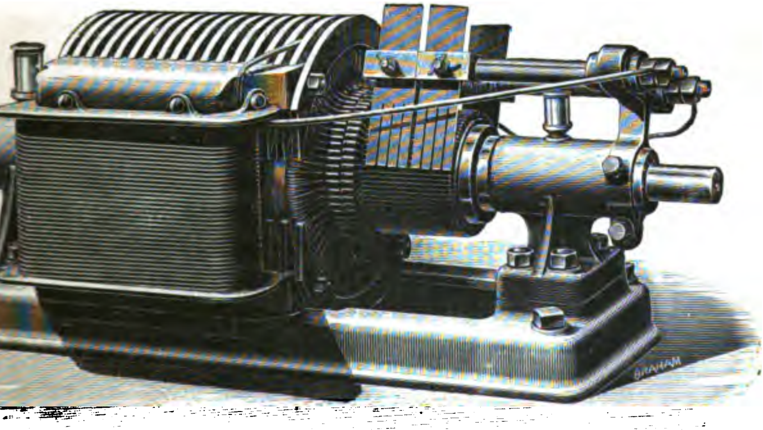
l is length of armature and d its diameter, in inches, the revolutions per minute.

might be supposed from the opening statement that scription of motors was superfluous. There are, how- ertain special forms of machine that have come into as motors, and are, therefore, described here.

rton and Perry's Motors.—Amongst the motors which t one time in commerce were special forms by Ayrton Perry, with a fixed external ring armature and an l revolving field-magnet. These motors were illus- in the earlier editions of this book. They had the ral defect of possessing too weak a field-magnet to them to run sparklessly, and though remarkably com- nd convenient, fell into disuse.

kenzaun's Motors.—Mr. A. Reckenzaun has developed gn of motor, with special reference to the require-

FIG. 388.

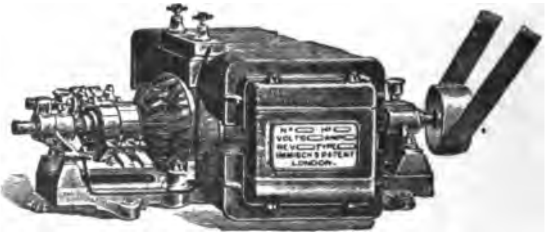


RECKENZAUN'S MOTOR.

of electric tramcars and launches. Cast iron, on t of the greater weight and dimensions, is here avoided, he field-magnets are built up of thick wrought-iron bent hot into such a shape as to form double horse- nagnets with the ends turned inwards. These ends are notched out to receive a series of segmental iron pieces which form the poles, as will be seen by the illustration (Fig. 388). This machine is light for its power, compact and strong. The entire height, for example, of a tramcar motor giving 8 HP. at 800 revolutions is only 13 inches; it weighs complete 600 lbs., and is capable of working up to 12 HP. (brake) for short periods. The armature, Gramme type, is 11 inches long. The section of the armature iron core is 10½ inches by $1\frac{7}{18}$ inches, and that of the field-magnet cores 9 inches by $1\frac{7}{18}$ inches. The magnets are series-wound, each limb containing two coils (in some cases three), which can be put in parallel or series so as to vary the exciting power and permit of obtaining the different rates of speed and power required in tramway work, without resorting to artificial resistances, and also of obtaining a great torque in starting, when all the coils are in series.

Immisch's Motors.—Mr. Moritz Immisch for many years constructed motors well known for their excellent mechanical construction, high efficiency, and great power in proportion to weight. Only those of smallest size have ring armatures, all others have drum armatures, and the field-magnets are usually of the double-horseshoe type, as shown in Fig. 389. A section of the machine, one-fifth of the full size, is shown in Fig. 390. The armature is 15 m. in diameter, and 1400 revolutions per minute gives 8 HP. on the shaft, with an efficiency of 85 per cent. It weighs only 350 lbs.

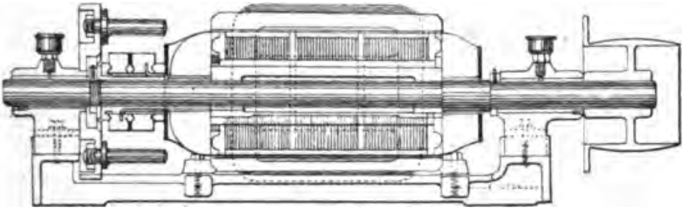
FIG. 389.



IMMISCH'S MOTOR.

The armature core consists of thin iron disks insulated with thin asbestos, having at the ends, and at intervals, thicker disks provided with projected driving-teeth, all the disks being securely keyed to the shaft. The windings are carefully insulated with Willesden paper protected with india-rubber varnish. The arrangement of the armature presents certain peculiarities, amongst which are the commutator connexions. The bars of the commutator or collector are grouped alternately in two sets, side by side, so that a single broad brush, or two brushes side by side in one holder, will always cut out of circuit the coil of the armature that is connected from the bar of the front set to the bar of the back set; the effect being exactly the same as if an ordinary collector were used with two pairs of connected brushes, those of each pair being set apart to a distance equal to the breadth of a single bar. The effect of cutting out the coils as they reach the neutral point is, according to the inventor, to diminish cross-magnetizing influences and obviate changes of lead; the brushes being set, once for all, in the required position. Some brake tests made in the presence of the author on a small ½-HP. motor, weighing about 20 kilogrammes (of which only about 3·5 kilogrammes were of copper), gave following results:—

FIG. 390.



IMMISCH'S MOTOR (Section).

Revolutions per Minute.	Volts.	Amperes.	E.HP. absorbed.	HP. given out.	Efficiency.
1420	40	10·5	·565	·354	·625
1840	49	10·5	·69	·46	·666
1920	50	11	·74	·48	·645
2280	61	12	·97	·57	·587

A large 30-HP. motor, weighing 850 kilogrammes, gave following results:—

Revolutions per Minute.	Volts.	Amperes.	E. HP. absorbed.	HP. given out.	Efficiency.
660	500	49	33	29·8	·90
680	500	48	32·2	29·5	·91
675	500	49	33	29·5	·89

The Immisch motors are now made by the General Electric Traction Co., whose engineer, Mr. A. T. Snell, has designed many large motors for traction and mining[1] purposes. In many of these motors carbon brushes, Fig. 277, p. 382, are now used. The mode of driving the core-disks of the large machines is shown in Fig. 251, p. 352.

The "Agir" Motor.—This motor, designed by Messrs. Andersen and Girdlestone (the "Industries" prize motor), is shown in Fig. 391, and its details of construction are given in full in Plates XVIII. and XIX. It was designed to meet the requirements of running at 250 revolutions per minute on 150 volt mains. It weighs 943 lbs., and when tested gave following results:—

Electrical HP. supplied	11·81	12·70	14·84
Speed of motor spindle	248	252	285
Mechanical HP. output	7·31	9·48	10·6
Nett efficiency	61·9	74·7	71·4

Brown's Motors.—Of these some mention is made in Chapter XXVI., and a large 4-pole motor of 240 HP. is described on p. 491.

Laurence, Paris and Scott's Motors.—Many firms now regularly supply motors of all sizes: this firm has kindly supplied the following particulars of a shunt-wound motor taking 10 amperes from 100 volt mains, and giving out a little over one actual HP.

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[1] See notes by Mr. Snell on Electrical Work in Mines, in *Proc. South Wales Institute of Engineers*, July 27, 1891. Also lecture on *Electricity in Mining* by author of this book, published by Messrs. Spon.

Armature 2-pole, drum-wound; diameter of armature core, 4½ inches, length of core, 4 inches; sectional area of iron in core, 7·6 square inches; number of segments of commutator, 36; turns per section, 10, No. 19, or 42 mm. wire; total number of turns, 360;

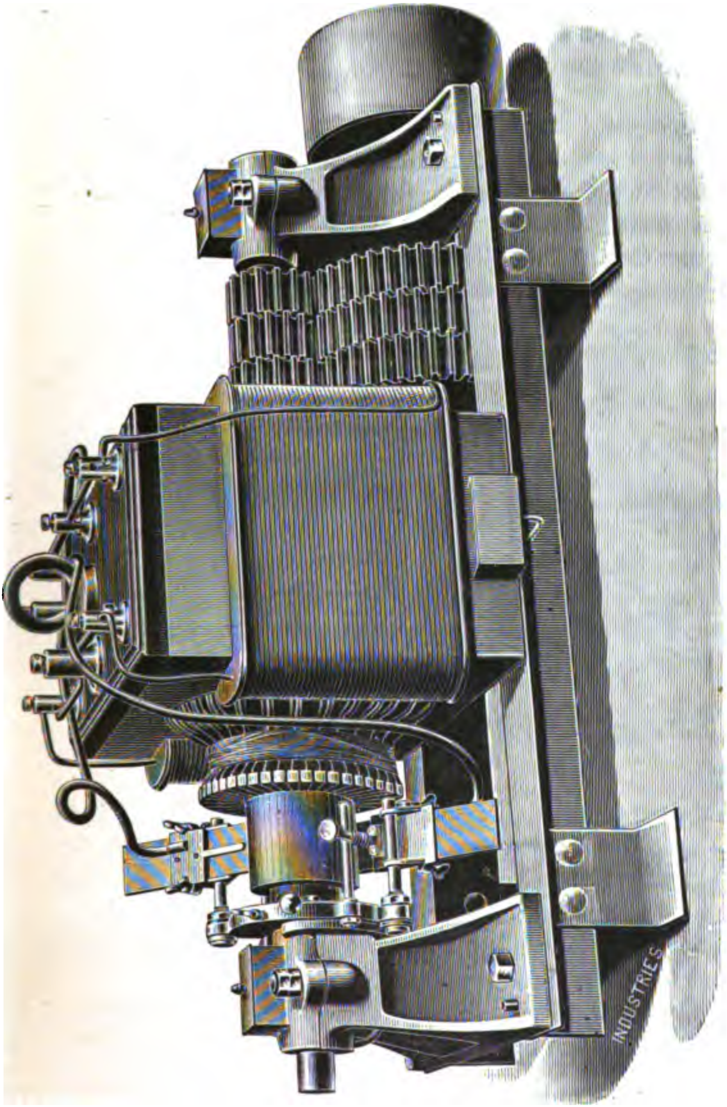


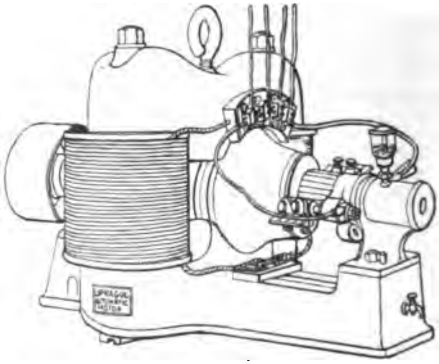
Fig. 391.

The "Agir" Motor (Andersen and Girdlestone's).

weight of wire on armature, 3½ lbs.; resistance of armature, 1·06 ohm (hot); magnet cast iron, 17·72 square inch area; shunt winding, 15 lbs. 9 oz., No. 23, or 25 mil wire, resistance 140 (warm); turns in shunt winding, 4960; starting coil on one limb only, 560 turns, No. 20, or 35 mil wire, 3 lbs.

Sprague's Motors.—Lieut. F. J. Sprague, of New York, has produced several forms of motor of excellent design and construction, many hundreds of them being in use in the States. One form of these machines is shown in Fig. 392. For further details the reader is referred to the accounts published in the technical press.[1] Sprague's method of winding the field-magnets with a differential compound winding is identical with that invented in 1883 by Ayrton and Perry, depending upon the use of a coil in series with the armature to demagnetize and weaken the field.[2] Many other ingenious methods of governing and practical applications have been worked out by Sprague.

FIG. 392.



SPRAGUE'S MOTOR.

Goolden's Mining Motor.—Mr. Atkinson has designed for Messrs. Goolden and Co. a mining motor of the same type as

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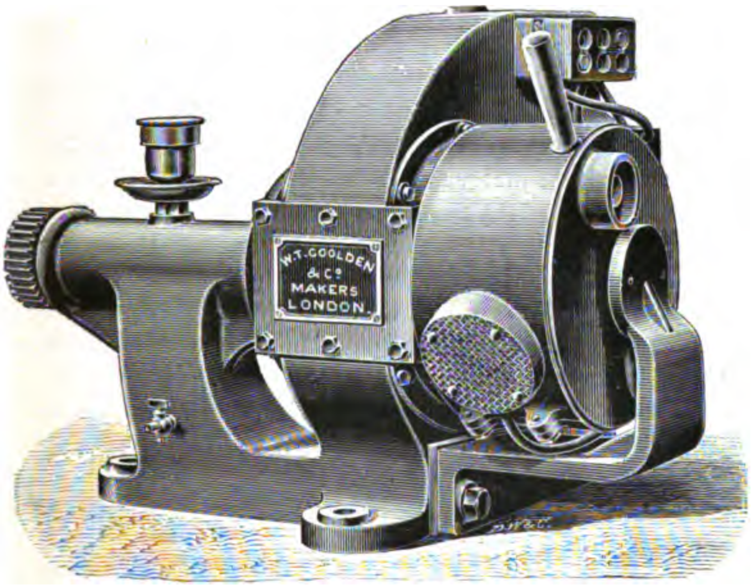
[1] *Electrical World*, October, 1886; also Martin and Wetzler's treatise on *The Electric Motor*, 157–75; and *Electrical World*, xiv. 3, 1889; xv. 370, 1890; also *The Electrician*, xxiv. 248, 1890.

[2] See Specifications of British Patents, Nos. 15,768 of 1884, and 3524 of 1885.

Fig. 121, p. 200, but with special adaptations for use in coal-mines;[1] the moving parts being enclosed so that all possibility is removed of a spark at the brushes causing an explosion. As shown in Fig. 393, the commutator and brushes, which are of carbon, are completely boxed in.

FIG. 393.



GOOLDEN ENCLOSED MINING MOTOR.

Electric Locomotive Motors.—Many motors have been designed for propelling tramcars and for electric railways; the points that inventors have chiefly considered being strong mechanical design of armature, slow speed with or without gearing, and construction that will resist deterioration by water, mud, dust, or overheating. Owing to the enormous rush of current just at starting, the armature must be capable of enduring the severest torque, and be practically fire-proof as well as water-proof. All gearings for speeding down have gradually fallen into disfavour, direct-driving slow-speed forms[1] being more reliable. All this implies the employment of motors with relatively powerful field-magnets. This is not the place to enter on a detailed account of electric locomotion in general or to describe any of the hundreds of electric tramways and railways now running. In Plate XX. is given a sketch of the electric locomotive of the City and South London subway railway, with two 50 HP. motors designed by Hopkinson. These are now being replaced by Siemens's locomotives of a pattern in which the field-magnets are relatively more powerful, enabling the armature to give the requisite torque with less current. A smaller example is afforded by the 20 HP. motor used in the Bessbrook Tramway, described by E. Hopkinson,[2] which ran at 100 revolutions per minute, taking 100 amperes at 220 volts. It was series-wound, the resistance of armature being 0·112 ohm, and of magnet 0·113 ohm. The nett efficiency was over 90 per cent. The field-magnet being very powerful, this motor is reversed by simply reversing current in the armature.

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[1] See the author's *Electricity in Mining*, p. 38, for descriptions of electric coal-cutters and other mining appliances.

Constant Current Motors for Arc Light Circuits.—For insertion in a series circuit special forms of motor are needed, most of them having governors of centrifugal type, to regulate the power taken from the mains; most of these are of American origin.[3]

Small-power Motors.—Several makers have given special attention to small-power motors for driving fans and other light running machinery. In England, Messrs. Cuttriss, of Leeds; in France, M. Trouvé; in Germany, various makers, in particular the Allgemeine Co., of Berlin; in the United States, Messrs. Curtis, Crocker, and Wheeler,[4] have all done good work.

Pulsating Motors.—The early type adopted by Page,

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[1] As a recent example, see the Thomson-Houston slow-speed motor described in *Electrical World*, xvii. 93, 1891.

[2] *Proc. Inst. Civil Engineers*, xci. part i., 1887-8.

[3] See *Electrical World*, xv. 269, 1890; xvii. 120 and 130, 1891; also *The Electrician*, xxv. 16, 45, and 131, 1890.

[4] See *Engineering*, xliv. 83, 1887; also *Electrical World*, ix. 4, 9, and 203; xiii. 309, 1889; xv. 114 and 269, 1890; xvii. 130, 191.

Hjorth and others, in which a purely reciprocating movement instead of a rotatory one was produced, has been revived in recent years for motors for the special purposes of operating hammers or drills. In 1879, Werner von Siemens[1] produced a mining drill in which a direct current and an alternating current of slow period were combined to produce a reciprocating movement without any commutator—a device lately revived by Atkinson and by Van de Poele. In 1880 Marcel Deprez[2] designed an electric hammer for forging, having a plunger of iron to be drawn up and down in a cylindrical coil wound in sections into which the current was successively led by a commutator.

Alternate Current Motors.—These are specially treated in Chapter XXIV.

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[1] D. R. Patent, No. 9469 of 1879 (see vol. ii. p. 389, of Siemens' *Arbeiten*).

[2] *La Lumière Électrique*, ix. 44, 1883.

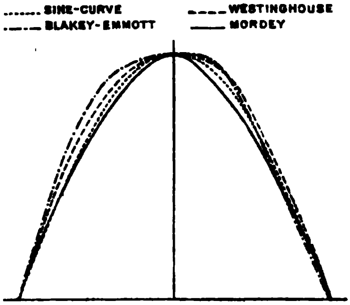
CHAPTER XXII.

THE PRINCIPLES OF ALTERNATE CURRENTS.

IN alternate-current working the current is rapidly reversed, rising and falling in a succession of impulses or waves. Electricity is in fact oscillating backwards and forwards through the line with enormous rapidity, under the influence of a rapidly-reversing electromotive-force. The adjectives *alternate, oscillatory, periodic, undulatory*, and *harmonic* have all been used to describe such currents. The author would prefer the term *wave-currents* as being both shorter and more apposite. The properties of alternate-currents differ somewhat from those of direct or continuous currents. They are affected not only by the resistance of the circuit but also by its inertia or self-induction, which diminishes the amplitude of the waves, retards their phase, and smooths them down in general. On account of these pecularities, some preliminary account of them is needed.

We have seen (p. 30) how the repeated approach and recession of a coil and a magnet pole will set up alternate electromotive-forces; and how (p. 213) the rotation of a simple loop in a uniform magnetic field will give rise to a truly periodic wave-current. We have seen also how the value of the periodic electromotive-force at any moment may be expressed in terms of the sine of the angle through which the coil has been turned. In the case of real machines in which the magnetic fields are not uniform, nor the coils simple loops, the periodic rise and fall of the electromotive-forces will not necessarily follow a simple sine law. The form of the impressed waves will depend on the shape of the polar faces, and on the form and breadth of the coils. .Consider the case of a machine in which the field-magnets consist of a double crown of opposing poles (as in the machines of Wilde, Siemens, Ferranti, Mordey, &c.). If the armature coils and magnet cores are both of circular form, and equal in diameter, as the coils approach the polar ends of the cores they will, it is true, gradually enter the field, and the number of lines cut by the coil during equal displacements will gradually increase and become a maximum when the axis of coil and core coincide, and from that point it will again decrease, almost in a sine law; the greatest rate of cutting being when the edge of the coil is opposite the centre of the core; but if coil and core be rectangular in outline, the greatest rate of cutting in each wire will be when one edge of the coil is passing the edge of the pole. In this case the sine law cannot be true for the electromotive-force. In order to test whether in any given dynamo the rise and fall of electromotive-force and of current in the armature coils conforms to the law of sines, experiments are necessary. Joubert, in order to measure the currents of a Siemens' dynamo, employed an electrometer method, and took off the current at any desired phase by a special commutator, and found an approximate curve of sines.[1] Another method, applicable also to direct-current machines, due to Mr. Mordey, is described.

FIG. 394.



CURVES OF ALTERNATORS.

In Fig. 394 are given four curves for a half-period. Of these one is a sine curve, the other three form actual alternators, showing how nearly they agree with a true sine curve. The one which agrees most nearly is that of the Mordey alternator, which lies just within the sine curve nearly throughout its whole extent. We are then sufficiently justified in assuming that the impressed electromotive-force follows a sine law, so that the electromotive-force at any instant may be expressed in the form—

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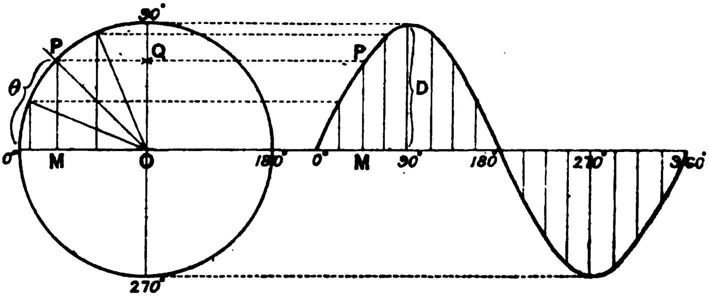
[1] For modern varieties of this method see p. 73, on which references are given. For the most recent research see paper by Dr. J. Linde in *Elektrotechnisches Echo*, No. 20, 1891.

$$E_\theta = D \sin \theta,$$

where D is the maximum value or *amplitude* attained by E, and θ an angle of *phase* upon an imaginary circle of reference. Consider a point P revolving clock-wise round a circle. If the radius of this circle be taken as unity, P M will be the sine of the angle θ, as measured from 0°. Let the circle be divided out into any number of equal angles, and let the sines be drawn similarly for each. Then let these sines be plotted out at equal distances apart along the horizontal line, as in Fig. 395, giving us the sine curve.

In Fig. 395 one revolution of P around the circle of reference corresponded to one complete alternation or cycle of changes. The value of the electromotive-force (which varies between + D and − D as its maximum values) may be represented at any moment either by the sine P M or by projecting P on to the vertical diameter, giving O Q. As P revolves, the point Q will oscillate along the diameter.

Fig. 395.



Curve of Sines.

There is yet another way of representing periodic variations of this kind, namely, by a diagram akin to that used by Zeuner for valve-gears. Let the outer circle (Fig. 396) be as before a circle of reference around which P revolves. Upon each of the vertical radii describe a circle. Then the lengths such as O Q, cut off from the radii, represent the corresponding values of the sine of the angle. If a card with a narrow slit cut radially in it were made to revolve over this figure, the intersection with the two inner circles would show the varying electromotive-forces in various positions.

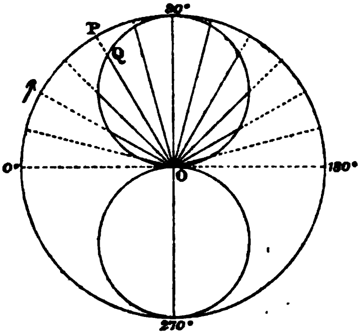


FIG. 396.

The reader who desires to pursue the graphic study of these matters further should consult the excellent treatise of Prof. Fleming,[1] or that of Mr. Blakesley,[2] and sundry papers by Mr. Kapp.[3]

We must now show how to calculate the rise and fall of current which the periodic electromotive-force sets up in the circuit. Those who are afraid of calculations should go on to the geometrical treatment of the problem, p. 627.

Analytical treatment.—To calculate this rise and fall we must remember that the motions of the rotating coils are supposed to take place with a uniform speed, and that the induced electromotive-force will be proportional to the rate of change in the number of magnetic lines induced through the circuit. To get a complete account of the action we must take into consideration the number of magnetic lines *induced by the circuit on itself.*[4]

Consider a simple loop of wire traversed by a current. Every portion of the loop will be surrounded by a whirl of magnetic lines similar to those of Fig. 13, and those belonging to the current in one-half of the loop tend to influence the current in the other half. Such influence or tendency of the current's lines to influence the other parts of the circuit is, however, only manifested when the strength of the current or the shape of the circuit is changing. We know that any increase in the number of magnetic lines that thread through a circuit (as, for example, by poking a magnet pole into it) tends to set up a current that will oppose the motion. Any increase in the strength of the current in the loop will increase the number of lines through the loop, and that increase will of itself tend to set up an opposing current. On the other hand, any decrease in the current in a circuit, by reducing the number of magnetic lines which thread through the circuit, tends to oppose the reduction of the current. A current, in fact, acts as if it had inertia, and tends to keep the number of its magnetic lines constant. This inertia of the current in a circuit is also known as the induction of the circuit on itself, or, briefly its self-induction. The self-induction in a circuit, which, as we have seen, is due to the number of magnetic lines threaded through the circuit itself by the current flowing in it, is always made up of two factors. When discussing the earlier case of the induction of a current in a loop by rotating it in a uniform magnetic field we neglected self-induction and considered the number of lines of force which were cut by the loop as being the product of two factors, viz. the total number of magnetic lines N that actually traverse

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[1] Fleming, *The Alternate Current Transformer*, London, 1889.

[2] Blakesley, *Alternating Currents of Electricity*, London, 1889.

[3] Kapp on 'Alternate Current Machinery.' *Proc. Inst. Civil Engineers*, 1889, pt. iii.

[4] Neumann's mathematical investigation of the effect of considering the self-

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induction of the circuit in relation to a periodic electromotive-force, was published in 1845, but self-inductive phenomena had previously been studied by Henry and by Faraday.

Other mathematical investigations of alternating electric currents have been given by Weber in his *Elektrodynamische Maasbestimmungen*, and by the following:—

Koosen, *Pogg. Ann.*, lxxxvii. 386, 1852.
Le Roux, *Ann. Chim. Phys.* [3], l. 463, 1857.
Clerk Maxwell, *Phil. Trans.*, 1865, p. 473.
Jamin and Richard, *Ann. Chim. Phys.* [4], xvii., 276, 1869.
Joubert, *Ann. de l'École Normale Supérieure*, x., 1881; and *Journal de Physique*, s. ii., t. ii., p. 293, 1883.
Lord Rayleigh, *Phil. Mag.*, May 1886. p. 375.
Hopkinson, Lecture at Instit. Civil Engineers (on Electric Lighting), 1883.
,, *Journal Soc. Telegr. Engineers*, xiii.
,, *Proc. Roy. Soc.*, Feb. 1887.

Abstracts of the most important of these will be found in Fleming's book on the *Alternate Current Transformer*.

the iron core of the armature, and C, the number of conductors at its periphery. In the case of self-induction the two factors will be different. The number of lines of force induced on itself by the current in a loop will be proportional to the strength of the current i. The number will, for a simple circular loop, be also proportional to the area of the loop. But for loops that are not circular, and for loops that consist of many turns, and for loops that have iron in them, a much more complicated investigation would be required than could be undertaken here if it were not for one fortunate circumstance. Suffice it to say that for a loop of many turns the coefficient of self-induction is proportional to the *square* of the number of turns. For each turn helps to produce magnetic lines and also adds to the "cutting" of the lines by the circuit. As a matter of fact, the two factors of self-induction are current i, and a quantity symbolized by the letter L, called "*the coefficient of self-induction,*" which represents the number of magnetic lines which the circuit would enclose or induce on itself if the current flowing in it were one "absolute unit." It follows at once that if current i flow through a circuit whose coefficient of self-induction is L, the whole self-induction of the circuit will be equal to L times i; and the product $L i$ will represent the total amount of enclosing of magnetic lines by the convolutions of the circuit. It will also be evident that if a current begins from strength 0 and grows uniformly until its strength is i, the *average* self-induction in the circuit will be $\frac{1}{2} L i$.

Returning now to the case of a loop having S_2 turns, placed at such an angle θ (measured from the initial position as in Fig. 134, where it stands right across the field), we see that it no longer encloses the whole number of magnetic lines which are present in the magnetic circuit. When we omit all account of self-induction, we may write

$$N_1 = S_2 N \cos\theta, \qquad \text{[I.]}$$

where N_1 is the virtual amount of enclosing of lines by the circuit.

But we know that if there is a current i in the circuit, we ought to write the equation in full—

$$N_1 = S_2 N \cos\theta + L\,i. \qquad \text{[II.]}$$

Our omission of the self-induction term in all the previous equations was only justifiable on the assumptions—firstly, that the field-magnets so overpowered the armature as to make the second term negligible; secondly, that the equations we obtained were the equations for *steady* currents.

Now we know that any variation in N_1 will set up induced electromotive-force, and that at any moment the electromotive-force will have the value

$$E = -\frac{dN_1}{dt}; \qquad \text{[III.]}$$

where we use the negative sign to show that an increase in N_1 will produce an inverse or negative electromotive-force. We are obliged to take note henceforth of the signs of the various quantities. Any change in N_1, from whatever source arising, will set up electromotive-force. We cannot well alter S_2, the number of coils of our armature. N can be altered; and in most modern alternate-current machines it is arranged that N, the number of magnetic lines in the field, can be controlled by hand or otherwise, the field-magnets of the alternate-current machine being usually separately excited by a constant current from a smaller dynamo, called the "exciter" (see Figs. 426 and 436). While the dynamo is at work, the coefficient of self-induction of the armature cannot be changed at will, as that depends on the size, shape, coiling, and coring of the armature, and on magnetic permeability; but it is possible to change the self-induction of the rest of the circuit. If we suppose this to remain constant then the only quantities that are really important in respect of the variations they will undergo—the only quantities whose variations contribute to the variations of N_1—are θ and i. The angle of position θ varies from 0 to 2π (radians); that is to say, from 0° right round to 360°, and then recurs; and its cosine therefore fluctuates between 1 and -1. The current i varies also from a certain maximum value $+ i_{\max}$ to an equal negative value $- i_{\max}$. We will neglect all the variations of the other quantities, not because these variations would not be instructive—for that would be quite untrue—but because of their lesser practical importance. Then we have

$$E = -\frac{dN_1}{dt} = -\frac{d(S_2N\cos\theta + Li)}{dt}.$$

Now suppose that while the armature loop has turned through the angle θ, the time occupied—a small fraction of a second—is t. Also take T to represent the time taken for one revolution; so that if there were n revolutions[1] per second, T will be $\frac{1}{n}$ of a second. Then obviously θ will be the $\frac{t}{T}$ part of a whole revolution, and as there are 2π radians in a circle, the angle expressed in radians will be

$$\theta = 2\pi\frac{t}{T} = 2\pi n t = \omega t;$$

where ω is the angular velocity.

Inserting this value, and performing the differentiation, we get

$$E = 2\pi n S_2N \, . \sin 2\pi n t - L\frac{di}{dt};$$

$$E = \omega S_2N \sin \omega t - L\frac{di}{dt}. \qquad \text{[IV.]}$$

Consider this equation carefully. It shows us that if there were an open circuit, so that there could be no i, then self-induction would not come in at all. Also if the motion were so slow that the rate of change of i were inappreciable, then the second term might be neglected. The negative sign also indicates that that part of the electromotive-force which is due to self-induction opposes the other part. Suppose we pause for a moment to consider the case of slow motion, and neglect the self-induction term; then we get

---

[1] For multipolar machines the number of alternations is more numerous than the number of revolutions in proportion to the number of pairs of poles. The symbol n will in this case stand for alternations.

$$E = 2\pi n S_2 N \sin\theta,$$

which is twice the value found on p. 231 for a direct-current machine in which the windings were not all in series, but grouped in two sets in parallel. Further, since the average value[1] of the sine between 0° and 90° is $\frac{2}{\pi}$, we get, as the average value of E,

$$E\ (\text{average}) = 4 n S_2 N.$$

Also it is important to notice, that with slow rotation, if the resistance of the circuit be R, the current will be at any moment

$$i = \frac{2\pi n S_2 N}{R}\sin\theta. \qquad [\text{V.}]$$

Now write D for the group of symbols $2\pi n S_2 N$, and we get—

$$i = \frac{D\sin\theta}{R}. \qquad [\text{VI.}]$$

We now pass on to entertain the case where the rotation is so quick that we must take in the self-induction term. Remember that though self-induction will set up perturbing electromotive-forces and diminish the impressed electromotive-force, yet if the nett effective electromotive-force at any instant is known the corresponding instantaneous value of the current can be calculated from it by simply applying Ohm's law. So if E, as found in formula [IV.], p. 626, be the effective electromotive-force, we may write $E = Ri$; whence

$$Ri = D\sin\theta - L\frac{di}{dt}.$$

---

[1] Or more strictly

$$\frac{1}{\theta}\int_0^\theta \sin\theta\, d\theta = \frac{1-\cos\theta}{\theta},$$

whence, if $\theta = \frac{\pi}{2}$, the average is $\frac{2}{\pi}$.

This is a differential equation of the form

$$a y + b \frac{dy}{dx} = \sin c x.$$

(See Boole's *Differential Equations*, p. 38.)

The solution is

$$i_\theta = \frac{D \cos \phi . \sin (\theta - \phi)}{R} + C \epsilon^{-\frac{R}{L}t}; \quad [VII.]$$

where ϕ is called the retardation or angle of *lag*, and has the value such that

$$\tan \phi = \frac{2 \pi n L}{R}.$$

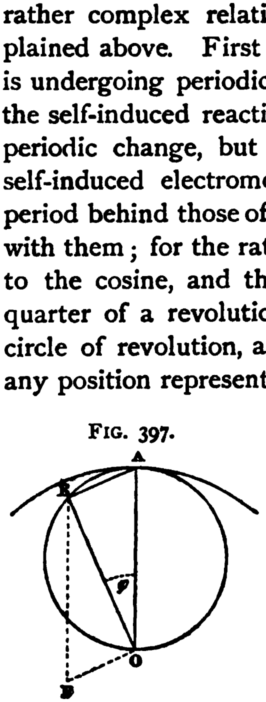
In the second term of the expression on the right-hand side of the above equation, the symbol C is a constant of integration, and ϵ is used in its common mathematical sense to represent the number 2·7182, which is the basis of the Napierian (or hyperbolic) logarithms. This second term may be omitted, because it relates only to the irregularities during the first starting of the current, and dies out as the time t increases in value. We have, therefore, got our equation for the current as follows:—

$$i_\theta = \frac{D \cos \phi . \sin (\theta - \phi)}{R}; \quad [VIII.]$$

which should be compared with the value that the current would have if there were no self-induction, as given in [VI]. We see by comparing the two expressions that our current still follows a sine-function, but it is the sine-function not of the angle θ, but of the angle $(\theta - \phi)$; that is to say, its waves *lag* behind those of the impressed electromotive-force. Also, the amplitude of the current is reduced, because everything is going on as if the amplitude of the impressed electromotive-force had been altered from D to D cos ϕ. Or, in other words, the effective electromotive-force is equal to the part of the impressed electromotive-force as resolved along the line of the lagging current.

Geometrical Treatment.—Another mode of studying these

FIG. 397.



rather complex relations is by the aid of the diagram explained above. First let it be understood how if the current is undergoing periodic changes, its rate of change (to which the self-induced reactions are proportional) will also undergo periodic change, but with the difference that the waves of self-induced electromotive-force will lag exactly a quarter-period behind those of the current, or will be "in quadrature"[1] with them; for the rate of change of the sine is proportional to the cosine, and the cosine is simply the sine shifted on a quarter of a revolution. Hence, when using in diagrams, a circle of revolution, as in Figs. 395 or 396, we have a line in any position representing the current or the effective electromotive-force which generates it, the line which is to represent the self-inductive reaction must be drawn at right angles —in quadrature—to the current. Let O A in Fig. 397 represent the amplitude of the impressed electromotive-force. Describe a circle upon O A, and on this circle take a point E, so that angle A O E = ϕ, and join A E, O E. A E O will be a right angle, and A E will represent the magnitude of the electromotive-force of self-induction when O E represents the current, or the effective electromotive-force which produces the current; the whole being considered to revolve about O, and the projections on the vertical line being taken as explained above. We have here two electromotive-forces, the impressed O A and the reactive A E (or O F, which is equal to it), with their resultant the effective electromotive-force O E, with an angle E O A, or ϕ, between them; the effective electromotive-force being equal to the impressed electromotive-force multiplied by cos ϕ. Let us now examine this angle ϕ which represents the lag of the effective electromotive-force (and therefore of the current) behind the impressed electromotive-force. We know that O E is equal to $R i$, and A E is equal to $2 \pi n L i$, being the maximum value of the rate of change of $L i \cos \theta$

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[1] This use of the term is due to Mr. Blakesley, *op. cit.*

(i. e. the maximum value of $2\pi n L i \sin\theta$). That is to say, A E is to O E as $2\pi n L$ is to R. Or,

$$\tan\phi = \frac{2\pi n L}{R}.$$

The quantity $2\pi n L$ is sometimes called the *inductance*, so that we may say the angle of lag is such that its tangent depends on the ratio of the *inductance* to the resistance. If we draw the triangle separately, as in Figs. 398, we may mark the values of the sides, the hypotenuse becoming $\sqrt{R^2 + 4\pi^2 n^2 L^2}$, a quantity sometimes called the "apparent resistance," or sometimes the "impedance."[1] We see then that $\cos\phi$ is equal to $R \div \sqrt{R^2 + 4\pi^2 n^2 L^2}$, so that equation [VIII.] p. 627, might have been written[2]

FIG. 398*a*.

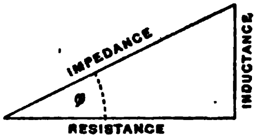
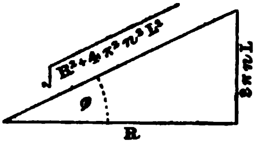


FIG. 398*b*.



= reactance

$$i_\theta = \frac{D\sin(\theta - \phi)}{\sqrt{R^2 + 4\pi^2 n^2 L^2}}; \qquad \text{[IX.]}$$

where we write the whole impressed (and retarded) electromotive-force as numerator, and the impedance as denominator,[1] instead of writing the effective resolved part of the electromotive-force as numerator, and the true resistance as denominator.

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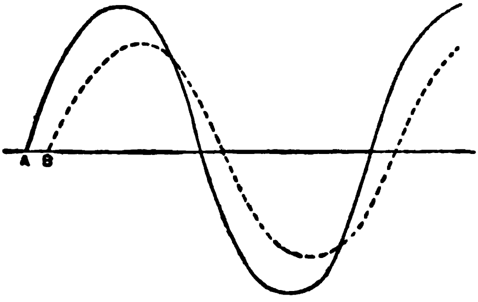
[1] The term *impedance* strictly means the ratio of any impressed electromotive-force to the current which it produces in a conductor (see Lodge's *Modern Views*, p. 398), of which the above is only one case. For steady currents the impedance is simply the resistance. For variable currents it may be made up of resistance, inductance, and (if the circuit has electrostatic capacity), of permittance, in various proportions according to the *form* of the variation. For true periodic currents obeying the sine-law the impedance is the square root of the sum of the squares of resistance and inductance. For currents which vary more suddenly the impedance will depend more on self-induction and less on resistance.

[2] This is indeed the classical way of writing it; and it was so written in the previous editions of this work. The whole notion of an apparent resistance, partly made up of real resistance and partly made up of an inductive reaction, is, however, awkward. The inductive reaction is not of the nature of a resistance, but that of an electromotive-force, which, compounded with the impressed electromotive-force, gives us a nett effective electromotive-force.

Before leaving Fig. 397 and the angle of lag, we may note that the lag is proportional both to L and to n; so that raising the frequency of alternations will exaggerate the two inductive reactions—will increase the lag and diminish or damp down the current. But increasing the resistance, though it diminishes the current, tends to lessen the lag. The effect of self-induction is then to *retard* the rise and fall of the current, so that it attains its maximum not when $\theta = 90°$, but when $\theta = 90° + \phi$, and ϕ cannot in any case exceed 90°, as will be seen by considering Fig. 397. Further, both the inductive reactions will increase with increased speed. There will be less lag, therefore, if the machine is so designed that it can be driven at a slow speed, or if the number of alternations per second be diminished, and if the coefficient of self-induction is small compared with the resistance of the circuit. This indicates that the number of turns of the coils in the armature part should be kept as small as possible, and the magnetic field made enormously powerful—a rule which applies equally to continuous-current dynamos.

FIG. 399.



These two inductive reactions, the lag and the damping of the current, may be summed up in a diagram, Fig. 399. Let the curve A represent the rise and fall of the induced current, as it would be if there were no self-induction. Then, since the tendency of self-induction in the circuit is both to retard the rise and fall of the effective electromotive-force, and to damp it down, it will have the effect of causing the current to rise and fall like the curve B, which has a smaller amplitude and is shifted along.

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[1] See Maxwell, *Phil. Trans.*, 1865, p. 473.

It may be remarked that mere retardation does not waste any of the power, nor does the mere introduction into the circuit of the opposing electromotive-forces of self-induction. If induction could be limited to these two effects, it would not be very prejudicial, it would simply make the machine act as a smaller machine. It lowers the plant-efficiency, but not the running-efficiency.

"*Virtual*" *Electromotive-force.*—Alternate-current voltmeters and alternate-current amperemeters do not measure the true average values of the volts and of the amperes. They measure what are called "virtual volts" and "virtual amperes." In a Cardew voltmeter the heating of the wire depends on the square of the current. In an electro-dynamometer the torque depends at every instant on the product of the currents in the fixed and movable parts; therefore, when used as an amperemeter, depends on the square of the current. The readings which these instruments give us, if first calibrated by using steady currents, are not true means, but are the square roots of the means of the squares. Now the mean of the squares of the sine (taken over either one quadrant or a whole circle) is $\frac{1}{2}$; hence the square-root-of-mean-square value of the sine functions is got by multiplying their maximum value by $1 \div \sqrt{2}$, or by 0·707. But we have seen that the arithmetical mean of the values of the sine is 0·637. Hence an alternating current, if it obey the sine law, will produce a heating effect greater than that of a steady current of the same average strength, by the ratio of 0·707 to 0·637; *i.e.* about 1·1 times greater. If a Cardew voltmeter is placed on an alternating circuit in which the volts are oscillating between maxima of + 100 and − 100 volts, it will read 70·7 volts, though the arithmetical mean is really only 63·7; and 70·7 steady volts would be required to produce an equal reading

The term *virtual*[1] has been used to denote these square-root-of-mean-square values. It may be remarked in passing that the virtual electromotive-force of a dynamo wound for alternate currents will therefore be 2·2 times higher (compare p. 651) than that of the same dynamo wound as an ordinary direct-current dynamo. The equations established above hold good, whether maximum or virtual values are used. For example, we may write

$$\text{Maximum } i = \frac{\text{maximum E}}{\text{resistance}} \times \cos\phi\,;$$

$$\text{Maximum } i = \frac{\text{maximum E}}{\text{impedance}}\,;$$

or

$$\text{Virtual } i = \frac{\text{virtual E}}{\text{resistance}} \times \cos\phi\,;$$

$$\text{Virtual } i = \frac{\text{virtual E}}{\text{impedance}}.$$

The diagrams of revolving lines may be drawn either with maximum or virtual values.

Mean Power.—The mean power is obtained by integrating the power during one period and dividing by that period, and therefore may be written

$$\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \mathrm{E}\, i\, dt = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \mathrm{R}\, i^2\, dt = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \frac{\mathrm{E}^2}{\mathrm{R}}\, dt.$$

Now if E and i were always in the same phase, the power at any moment would be simply the product of their values at that moment, and the mean power would be the product of their virtual values, or the half of the product of their maximum values.[1] But if there is a lag ϕ between them, then the product at each instant must be multiplied by cos ϕ. So that

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[1] I adhere to the term *virtual;* it was in use before the term *effective* which was recommended in 1889 by the Paris Congress to denote the square-root-of-mean-square value. I adhere to it mainly because the adjective *effective* is required in its usual meaning in kinematics to represent the resolved part of a force which acts obliquely to the line of motion, the effective force being equal to the whole force multiplied by the cosine of the angle at which it acts with respect to the direction of motion.

$$\begin{aligned} \text{Mean power} &= E_{\text{virt.}} \times i_{\text{virt.}} \times \cos\phi, \\ \text{,,} \quad \text{,,} &= \tfrac{1}{2} E_{\text{max.}} \times i_{\text{max.}} \times \cos\phi, \\ \text{,,} \quad \text{,,} &= i^2_{\text{virt.}} \times R, \\ \text{,,} \quad \text{,,} &= E^2_{\text{virt.}} \div R. \end{aligned}$$

If we square the expression [IX.] found for current and substitute for the square of the sine its mean value $\tfrac{1}{2}$, and then multiply by R we get as the mean power (in watts)

$$W = \frac{2\pi^2 n^2 S_2^2 N^2 R}{R^2 + 4\pi^2 n^2 L^2};$$

and this expression, by a well-known algebraic rule, will be a maximum for variations of R when R is such that the two terms in the denominator are equal, or when the resistance equals the inductance. Under these circumstances the lag is 45°. But though this is the condition for highest plant efficiency, the regulation is, under these circumstances, bad. Hence it is better to use such a machine for lesser currents than those which would produce so great a lag.

Numerical Example:—Let an impressed electromotive-force of 65 (virtual) volts, alternating with a frequency of 50 periods per second, act upon a circuit having resistance 1·5 ohm, and a coefficient of self-induction of 0·002 henry. Find the lag, the current and the mean power.

To find the lag, we must find the inductance, $2\pi n L$, and divide this by the resistance; or

$$\tan\phi = 2\pi n L \div R = 2 \times 3{\cdot}1416 \times 50 \times 0{\cdot}002 \div 1{\cdot}5 = 0{\cdot}419.$$

Looking in a table of natural tangents, we find that ϕ will be 22° 44′; whence a table of natural cosines gives us cos ϕ = 0·9223. Or, we might calculate cos ϕ directly as $R \div \sqrt{R^2 + 4\pi^2 n^2 L^2}$. Multiplying cos ϕ into the 65 volts, we get 59·95, say 60, as the effective virtual volts, and dividing by the resistance, gives 40 virtual amperes as the current. The mean power is $65 \times 40 \times 0·9223 =$ 2400 watts.

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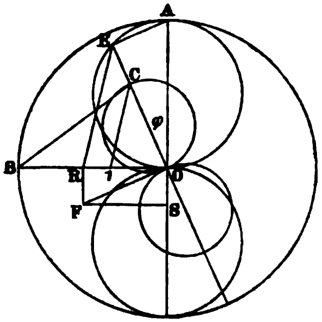
[1] On the question of measurement of the mean power of alternating currents, see papers by Prof. Ayrton and others in *Phil. Mag.* and in *Proc. Roy. Soc.* in 1891, copied into most of the technical journals; also papers by Swinburne and Blakesley. Blakesley's method of the three electrodynamometers, and Ayrton's method of the three voltmeters, ought to be known to every person who requires to measure power in alternate current circuits and machines.

Geometrically this is given in Fig. 400.

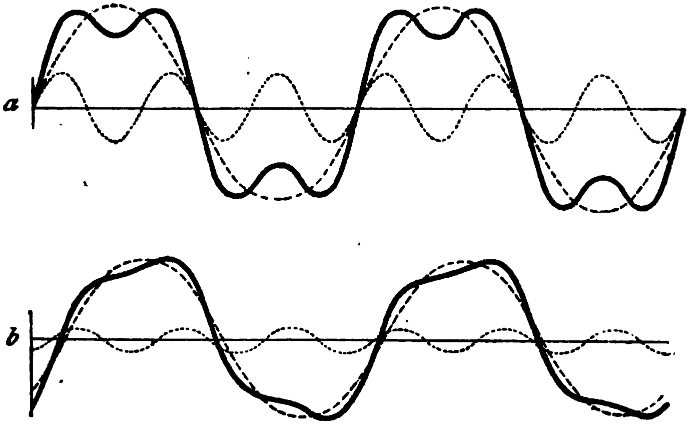
Let O A be 65 to any scale, the impressed (virtual) volts. Describe the circle of radius O A, and the semicircle O E A. Draw O B at right angles to O A. On O B set off O R on any convenient scale of resistance, O 1 being taken as 1 ohm. Using same scale, set off O S or R F at right angles, equal to the inductance $2\pi n L = 0·628$. Join O F. R O F is the angle of lag. Draw E O at right angles to O F, cutting semicircle in E. E O A is also angle of lag, hence E O represents effective virtual volts; and A E the cross-electromotive-force of self-induction $2\pi n L i$. Join E R and from 1 draw 1 C parallel; C O will represent the current. As O B is O A turned through a right angle, the area of triangle B O C $= \frac{1}{2}$ O A·O C· cos A O C $= \frac{1}{2}$ mean power.

FIG. 400.



We are now in a position to explain why it is desirable that the induction curves of alternators should follow the sine-form, and why wide departures therefrom are undesirable. According to the well-known theorem of Fourier, every complex single-valued periodic function can be analyzed down into a series of simple periodic functions differing in amplitude and phase, but all belonging to a harmonic series, having frequencies that are some exact multiple of a single fundamental frequency. Every complex wave curve may be regarded as built up of sine curves. For example, the curve shown in Fig. 401*a* may be looked upon as a compound of the two dotted sine curves, one of a frequency three times that of the other. Now, if this complex curve represents the impressed electromotive-force of an alternator with curiously-shaped poles, what will the curve of effective electromotive-force (or of current) be when self-induction is present? The amplitude is cut down in proportion nearly to the frequency of the alternation. Hence the component ripple, which has three times the frequency, will be damped out nearly three times as much as the fundamental wave.[1] In Fig. 401 *b* are shown the two waves, as altered by a lag of 41°, which cuts down the fundamental to 0·75, and the ripple to 0·35 of their respective amplitudes; the resultant wave being also shown. It is evident that self-induction tends to smooth out the ripples, including all parts of the wave that do not fit to the sine form. Hence those alternators which give induction curves of true sine form are less affected by self-induction than others, regulating better, and having a higher plant-efficiency.

FIG. 401.



Alternate Currents in relation to Capacity.—If a condenser is interposed in the circuit of an alternator, an alternate current will play into and out of the condenser, charging it in alternate directions. The action of the condenser's capacity on the current is best summed up by saying that it acts like a negative and reciprocal inductance. If K be the capacity of the condenser (in farads), and the frequency be n, then it will act like a (negative) inductance of $- 1 \div 2 \pi n K$ henries. The effect, therefore, of a capacity in series with the circuit is to accelerate the phase of the current, producing a lead instead of a lag in the current. A capacity acting laterally across the circuit, as when a condenser is placed across the two mains, has the effect of increasing the flow of current from the dynamo up to the points on the circuit which are connected to it, and therefore of raising the virtual potentials of those points, thereby affecting the voltage of the rest of the circuit. There is, for a given frequency, resistance and self-induction, one particular value of capacity which would enormously increase the current and voltage as by a sort of resonance. These various condenser effects have been considered by various writers. A very clear exposition of them, together with the phenomena observed on the Ferranti mains on the Deptford supply has been given by Fleming.[1]

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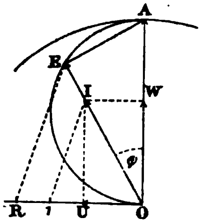
[1] See investigation by Ayrton and Perry in *Journal Inst. Electrical Engineers*, xviii. 300, 1889.

Watt-less Current.—Whenever there is a great phase difference between volts and current (whether a lag due to self-induction or a lead due to capacity), the true watts are, as has already been pointed out, much less than the apparent value that would be obtained by merely multiplying together the virtual amperes and the virtual volts. For, as we have seen, this product must be further multiplied by the cosine of the angle of lag (or lead). Now there are two ways of looking at this matter, the product $E_{\text{virt}} \times i_{\text{virt}} \times \cos\phi$ may be regarded as either the product of the virtual amperes into the resolved part (or effective part) of the virtual volts, or it may be regarded as the product of the virtual volts into the resolved part of the virtual amperes. Just as any force may be resolved into two component forces at right angles to one another, so any alternating current may be resolved into two component alternating currents differing 90° in phase. Or i may be resolved into two parts, $i \cos\phi$ agreeing in phase with the volts, and $i \sin\phi$ in quadrature with the volts. These two resolved parts of the current may be termed the *working-current* and the *watt-less current.* In Fig. 402 O E represents the effective part of the impressed electromotive-force O A. Of O E a part O I is found, as described on p. 634, to represent the current i. Of this current the resolved part O W, in phase with O A is the working current, and the part O U, which is in quadrature with O A, is the watt-less current. Whenever, for either cause, the angle of lag is great, the watt-less part of the current will be great also. For example, when transformers are left on open circuit, the current in the primary is nearly in quadrature (owing to self-induction) with the impressed volts, and, if it were not for hysteresis or eddy-currents in the iron cores, would be almost entirely watt-less.

FIG. 402.



For example, if there is a current of 100 virtual amperes lagging 14° behind the impressed volts, this may be resolved into a working current of 97·03 virtual amperes, and a watt-less current of 24·2 virtual amperes.

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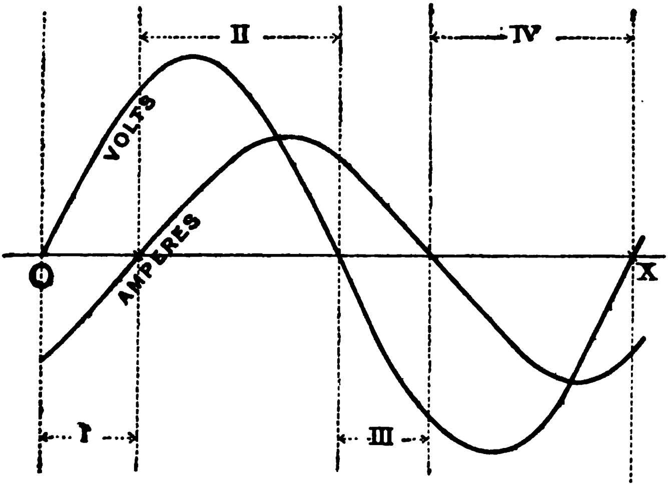
[1] *Journal Inst. Electr. Engineers*, xx. 362, 1891.

High Frequency Alternations.—Alternations of very high periodicity, going up to as many as 10,000 or 20,000 per second, have been studied by Spottiswoode,[1] and more recently by Tesla,[2] who has obtained some very remarkable effects. One of his alternators was of the same type as Mordey's, having numerous polar projections on either side,[3] and another was of the inductor type. With these excessively high frequencies the currents flow almost exclusively along the surface layers of conductors, instead of flowing through their entire cross-section; even straight rods of copper offering a relatively enormous impedance.

Torque of Alternators.—A very singular result follows the presence of any lag in the current of an alternator. It was pointed out on p. 554, that where amperes flow with the volts, electric energy is being supplied by the machine, and power must be applied to drive it; but that when amperes flow against a counter electromotive-force, there electric energy is leaving the circuit and being turned

FIG. 403.



EFFECT OF LAG OF CURRENT.

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[1] *Proc. Roy. Soc.*, xxiii. 455.

[2] *American Inst. Electrical Engineers*, May 1891. See *Electrical World*, xvi., 1891, and *The Electrician*, xxvi., 549, 1891.

[3] See *Electrical Engineer* (N.Y.), March 18, 1891.

into mechanical energy, helping to drive the machine. The one is the case of the generator, the other that of the motor. But now consider an alternator with the amperes lagging behind the volts, as indicated by the diagram of Fig. 403. It is clear that in consequence of this lag the amperes are sometimes flowing against the volts instead of with them. In fact, we may divide each complete period such as O X into four parts, during two of which, namely II. and IV. in Fig. 403, the amperes and volts are alike in direction, either both positive, or else both negative; during the other two parts—namely I. and III.—the amperes and volts are opposed in direction because the volts have reversed in sign, but the lagging amperes have not yet changed. Now during the partial periods II. and IV., when there is agreement in sign, the machine is in the condition of being a generator, and will require to be driven, the currents in the armature setting up a counter torque. But during the other partial periods I. and III., when there is opposition in sign, the machine is in the condition of being a motor, and will tend to drive itself, the torque helping it on. The conductors are consequently subjected to a racking action, alternately resisting, being driven and then helping to drive twice in each period. It is clear that if there is little lag there will be little motor action, the partial periods I. and III. being brief; whereas if there is much lag the motor action will increase. If there is a lag of exactly a quarter of a period, the motor and generator actions will be equal. Similarly, if in consequence of capacity the current leads in phase, there will be motor action in partial periods. This subject may be considered in another way. The electromotive-forces change sign just as the conductors are passing (for example, take Fig. 412, p. 646) from one magnetic field into another, where the lines run in an opposite direction. If the currents are in phase with the electromotive-forces, they will always tend to oppose the motion that generates them. But if they lag then after the conductor has passed from one field to the other until such time as the currents have reversed, they will be helping on the motion.

Measurement of Power in Alternating Circuits.—On this important topic see remarks on p. 633.

CHAPTER XXIII.

ALTERNATORS.

ALTERNATORS, or alternate-current dynamos, may be classified in three sorts :—

I. Those with stationary field-magnet and rotating armature.

II. Those with rotating field-magnet and stationary armature.

III. Those with both field-magnet part and armature part stationary, the amount of magnetic induction from the latter through the former being caused to vary or alternate in direction by the revolution of appropriate pieces of iron, called *inductors.*

Alternators may also be classified according to whether they give simple two-phase currents, or are multiphase.

In all alternators the electromotive-force rises and falls in a rapid periodic fashion, a wave of electricity being forced through the circuit, first in one direction, then in the other, with very great rapidity. The time taken for one complete alternation to-and-fro of the current is called one *period.* The number of such complete periods or double-reversals of the current in a second is called the *frequency*, or sometimes the *periodicity*, of the alternations. The frequency used in practice varies between 40 periods per second to 100 or sometimes 150 periods per second ; but each machine is expected to work at its own proper frequency. The symbol ∼ is sometimes used for the frequency instead of the letter n. Thus, 100 ∼ stands for a frequency of 100 complete periods per second, *i. e.* 100 positive currents or half-waves, each followed by a negative half-wave. The symbol n used for the number of revolutions per second in the formulæ for direct-current dynamos is also used for the number of periods per second in formulæ for alternate currents; as it corresponds to the number of complete alternations there would be if the dynamos had but one pair of poles. As it is requisite in alternate-current working to have so many alternations in every second, and as mechanical considerations forbid very high speeds, it is the general practice to make this class of machines multipolar, with a considerable number of poles of alternate polarity arranged symmetrically around a common centre. The number of symmetrical poles in machines of different systems varies from 12 to 48, or more.

The armatures of alternators may be of ring, drum, pole, or disk type; but in all cases the grouping of the windings is different from that which would be adopted for a direct-current dynamo. The field-magnet being multipolar, a section of the armature winding which is passing a N-pole will have currents induced in it that circulate in an opposite sense to those induced in a section which is at the same moment passing a S-pole. Hence in an alternate-current ring the successive sections must be either wound or connected so as to be alternately right-handed and left-handed. In alternate-current drums the sections do not overlap one another as in ordinary drum armatures; nor do they overlap in alternate-current disk armatures.

Ring Armatures.—This type was invented in 1878, almost simultaneously by Gramme[1] and by Wilde,[2] the main difference between them being that, whilst Gramme rotated his field-magnet within a large stationary ring, Wilde rotated his ring armature within an external system of inwardly pointing field-magnet poles (see Fig. 120, No. 28). When ring armatures are used in this type of dynamo, they must not be wound in the same manner as for continuous-current armatures. If the successive sections are to be connected up consecutively, then they must be wound, as shown in Fig. 404, alternately with right-handed and left-handed windings. If all the sections are coiled right-handedly, then they must be connected, as shown in Fig. 405; for the electromotive-force induced in a coil as it passes under a north pole will circulate around the armature core in an opposite direction to that

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[1] Specification of Patent, 953 of 1878.

[2] Ibid., 1228 of 1878.

FIG. 404.

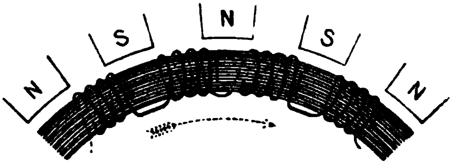
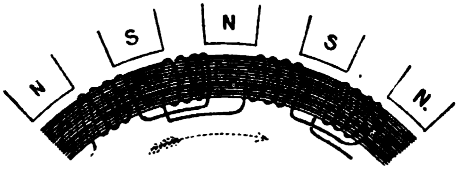
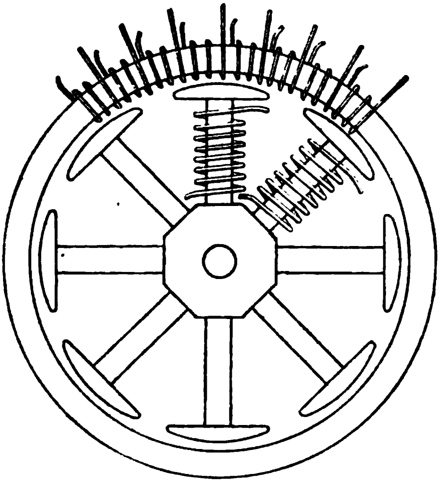


FIG. 405.



RING-ARMATURE WINDINGS FOR ALTERNATORS.

FIG. 406.



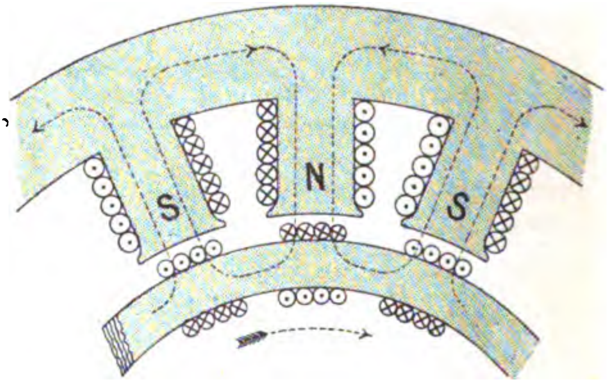
GRAMME ALTERNATOR.

induced in the neighbouring coil that is passing under a south pole.

A diagram of the Gramme alternator is shown in Fig. 406

The sections of the winding of this machine were four times as numerous as the poles, and might be coupled to feed four separate circuits. It is clear that the revolving poles would come past the four adjacent sections successively, so that the four alternating currents generated would differ *in phase* from one another. One form of Gramme alternator, designed for use with Jablochkoff's candles, and made auto-exciting by the addition of a small direct-current dynamo on the same shaft, was depicted in the former editions of this book. Another ring alternator, by De Meritens, with permanent steel magnets was a favourite about 1879. Another design, with external magnet, is shown in Fig. 407, which closely resembles the form used by Messrs. Ernest Scott and Mountain. In this figure, the magnetic circuits are traced to guide the designer in calculating out the exciting power. It will be noticed that the inner wires of the ring perform no active inductive part; also that the currents in adjacent sections flow reversely.

FIG. 407.

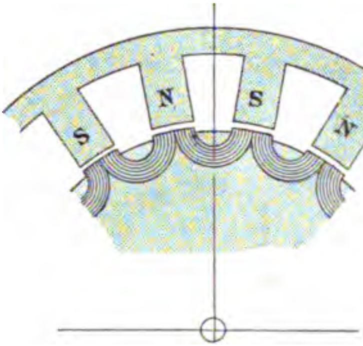


MAGNETIC CIRCUITS OF ALTERNATOR.

In Kapp's alternator, Fig. 421, p. 655, the ring lies between a double crown of field-magnet poles. Other ring alternators have been designed by Kennedy, who uses a discoidal ring between alternately-spaced alternate poles within an iron-clad magnet; and by Mordey who has suggested a form with two Pacinotti rings, one laminated as armature, one non-laminated, as field-magnet.

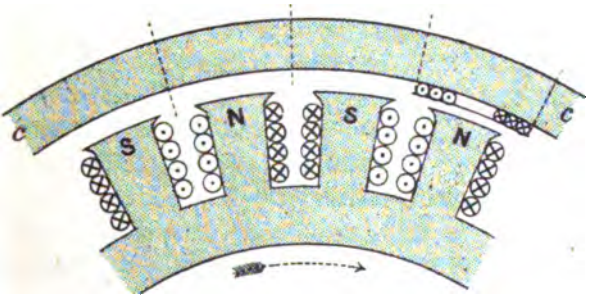
Drum Armatures.—A glance at Fig 407 will show that, so far as the active wires are concerned, they might be coupled up quite as effectively without being wound around a ring core. In Fig. 408, which is a diagrammatic picture of the Westinghouse alternator, the windings lie on the outside of a drum-core; the sections being coiled separately on temporary frames and then laid upon the surface of the core, with the ends turned down over the end core disks and firmly secured.

FIG. 408.



WESTINGHOUSE ALTERNATOR.

FIG. 409.

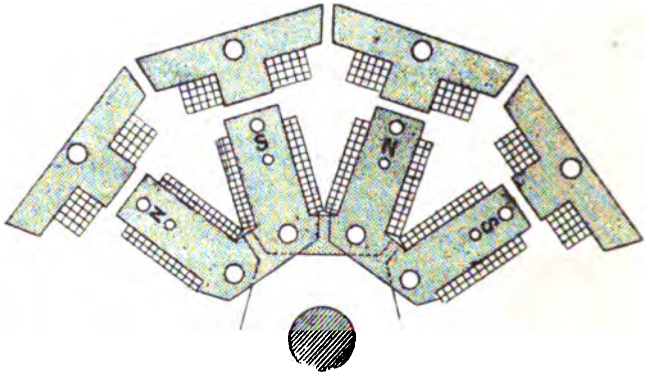


ELWELL-PARKER ALTERNATOR.

It is but a step from this form to that of Fig. 409, which has an internal revolving field-magnet, and as armature an external cylinder built of segmental core-plates, against the inner periphery of which the armature coils are fastened.

Again, it is but a step from this form to Fig. 410, which shows the construction of Zipernowsky, in which the field-magnet cores are made up of U-shaped stampings, and the armature cores of short T-shaped pieces which project through the coils, and are removable singly. We are thus passing away from the drum type toward that with pole armature.

FIG. 410.

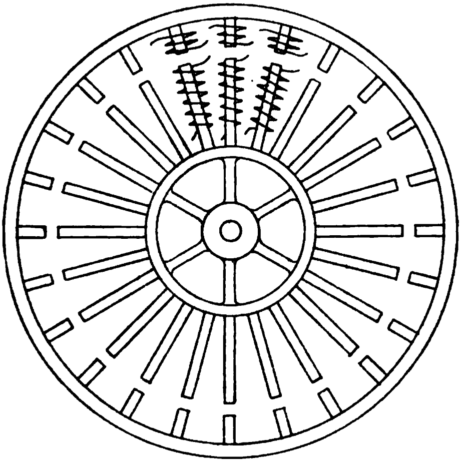


GANZ-ZIPERNOWSKY ALTERNATOR.

Pole-Armatures.—The typical pole-alternator is the now obsolete machine of Lontin, a skeleton diagram of which is given in Fig. 411. In this machine the field-magnet (separately excited with a continuous current) consisted of a set of radiating poles, and it rotated within an outer set of coils which served as a fixed armature. These coils were wound upon short cores of solid iron. This machine had many defects, not the least of which was the great mass of iron in which so many internal eddy currents were induced that the machine was very prone to become overheated. Indeed, it required more power to drive it on open circuit than when the machine was supplying its maximum number of lamps.

A modification of this machine, having laminated iron cores in the armature part, has been used by Kennedy and others. Hopkinson's alternator, Fig. 425, p. 664, is an inversion of this design, the field-magnet being fixed and external.

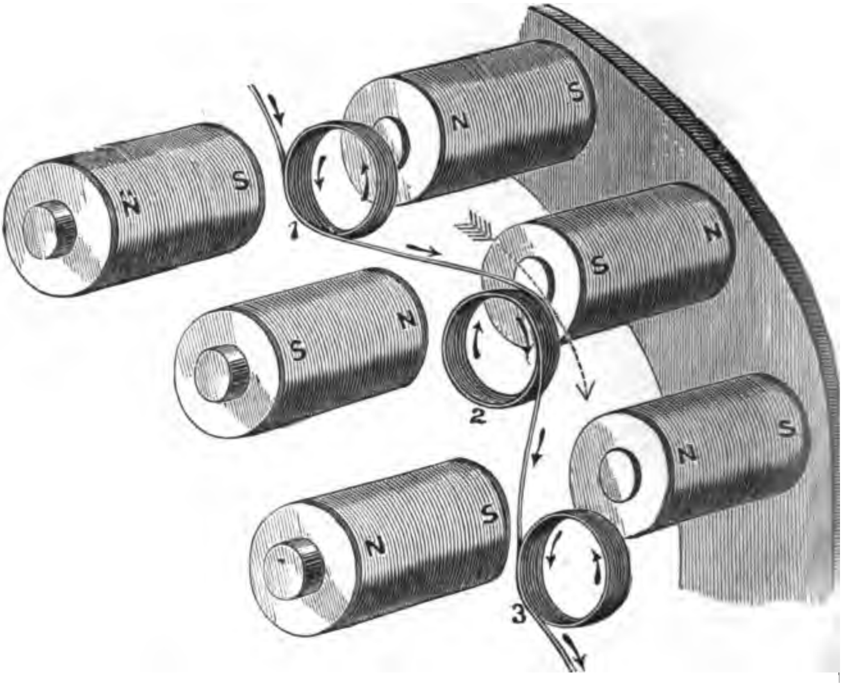
FIG. 411.



PRINCIPLE OF POLE ALTERNATOR.

Disk Armatures.—In these machines the armature coils are arranged around the periphery of a disk. The old machines of Nollet and Holmes, and the so-called "Alliance" machine (all of which had permanent magnets of steel), belonged to this class. The more modern type, with electro-magnets, was created by Wilde, in 1867. The field-magnets consist of two crowns of fixed coils, with iron cores arranged so that their free poles are opposite to one another, with a space between them sufficiently wide to admit the armature, Fig. 412. The poles taken in order round each crown are alternately of N and S polarity; and opposite a N-pole of one crown faces a S-pole of the other crown. This description will apply to the magnets of the alternate-current machines of Wilde and Siemens, and to Ferranti's alternator. The principle will be best understood by reference to Fig. 412, which gives a general view of the arrangement. Since the magnetic lines run in opposite directions between the fixed coils, which are alternately S—N, N—S, as described above, the moving coils will necessarily be traversed by alternating currents; and as the alternate coils of the armature will be traversed by currents in opposite senses, it is needful to connect them up, as shown in Figs. 416 or 417, so that they shall not oppose one another's action. In Wilde's alternator, the armature coils had iron cores, and the machine was provided with a commutator on the principle indicated in Fig. 419, p. 652. This commutator Wilde usually applied to a few, or only one, of the rotating coils, and utilized the current thus obtained to magnetize the field-magnets. The two contact-rings for collecting the main current are also shown in the figure.

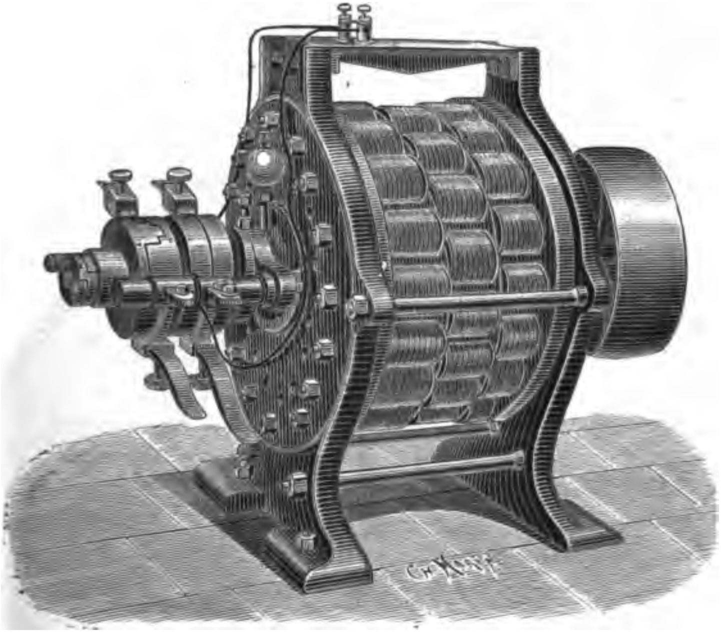
FIG. 412.



PRINCIPLE OF DISK ALTERNATOR.

Siemens improved the design in 1878, by omitting the iron from the cores of the armature, which he narrowed greatly, thus diminishing its reactions. Ferranti's alternators follow the same plan, the copper coils being built up into a thin disk, as indicated in Figs. 414 and 415.

FIG. 413.



WILDE'S ALTERNATOR.

FIG. 414.

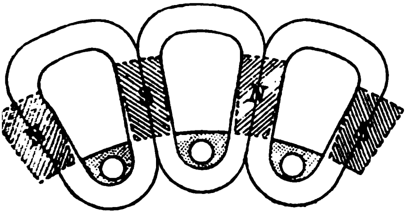
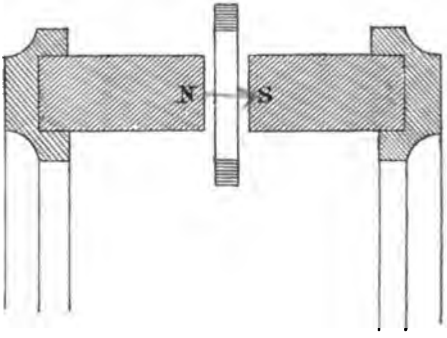


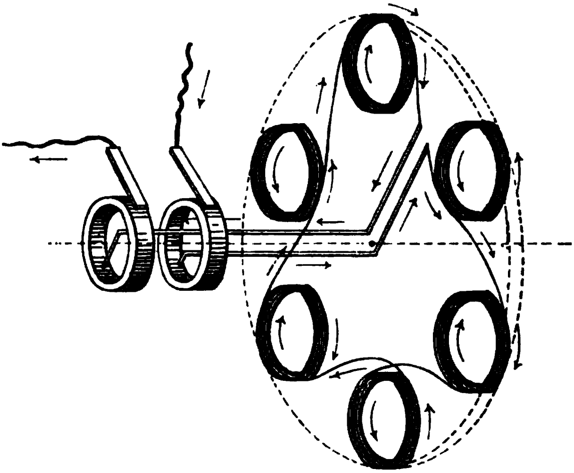
FIG. 415.



FERRANTI'S ALTERNATOR.

Collecting-Rings.—For collecting the main current of the alternator, extremely simple means are required. In those machines in which the armature part is fixed, mere terminals are required. In machines with rotating armatures simple sliding connexions are required. The usual method of collecting is shown in Fig. 416. Two undivided insulated metal rings, forming the terminals of the armature coil, slide each under a single collecting-brush.

Fig. 416.

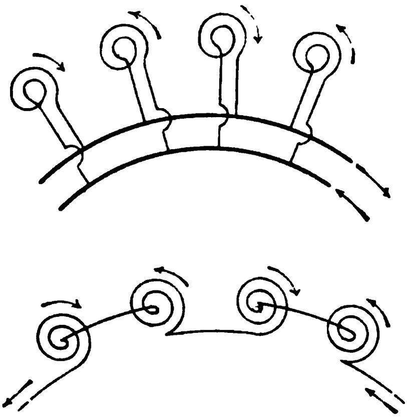


COLLECTING-RINGS OF ALTERNATORS.

Where high voltages are used the two contact rings should be so placed that by no accident can an attendant touch both at the same time. It is also well to provide two brushes to each ring. For alternators with stationary armatures a similar but smaller pair of contact-rings suffice to carry the exciting current to the revolving field-magnets. The special devices of Ferranti for collecting are described later.

Coupling Armature Coils.—There are various ways of coupling up the coils of alternators, according to their purpose. For low voltage work the coils may be coupled up in parallel as in Fig. 417, so as to reduce the internal resistance; whilst for supplying distant transformers and for transmission of power, in both of which cases high electromotive-force is required, the more usual mode of connecting is to join the several coils in series, as in Figs. 416 and 418. In Chapter XII., on the theory of armature winding, it was shown (see Figs. 202 and 203) how either a lap-winding or a wave-winding might be applied to an alternator. The use of a wave-winding for this purpose was suggested almost simultaneously, in 1881, by Sir William Thomson, and by Mr. Ferranti. But there are disadvantages in its use for high voltages, owing to the difficulty of maintaining the insulation between each "wave" and the succeeding one, and it has been abandoned in favour of a lap-winding, in which each coil can be well insulated by itself from its neighbours. In some alternators —including those of Ferranti and Westinghouse—the coils are joined in two parallels, not all in series, a construction which has the result of keeping the points of greatest potential difference widely apart.

FIGS. 417, 418.



DIFFERENT MODES OF COUPLING UP ARMATURE-COILS OF ALTERNATORS.

WIDTH OF POLE FACES AND BREADTH OF ARMATURE WINDINGS.

The distance from the centre of one N-pole to that of the adjacent S-pole may be called the *pitch* of an alternator. It is desired to know what is the best proportion for the pole-faces and the windings to bear to the pitch. This matter has been discussed by Kapp.[1] It involves two questions—(1) in what way will the voltage depend on the relative width of poles and breadth of windings; (2) what proportions will give the highest plant-efficiency. If the poles are too wide, so as nearly to touch, not only is there great leakage, but the coils must be inconveniently crowded. It is obvious that for any coil to give its best result it should be so large as to embrace the whole flux of magnetic lines from each pole as it passes. If it is smaller, it contributes less to the total voltage. If it is larger it merely takes more space. Hence it is usual to make the width of the internal aperture of the coils but little less than the width of the pole, and to make the external width equal to the pitch. Compare Figs. 407, 408, and 409, in the first two of which the inner width is rather less, and in the third rather greater than that of the pole-faces, whilst the double breadth of copper in the coils is about equal to the width of the poles.

It has been shown on p. 211 that the average electromotive force of a continuous current dynamo may be written

$$E = n \, C \, N \div 10^8;$$

where n was the number of revolutions per second, C the number of conductors around the armature, and N the magnetic flux. We may adapt this to alternators, whilst keeping the two former symbols, and using N for the magnetic flux through any *one* pole, by multiplying by p the number of pairs of poles, and by a coefficient k.

So we have

$$E \text{ (virtual volts)} = k \, p \, n \, C \, N \div 10^8.$$

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[1] *Proc. Institution Civil Engineers*, xcvii. 1889, pt. iii.

If the fluctuations follow a sine curve, so that the virtual volts are 1·1 times greater (see p. 631) than the average volts, the coils are all joined in series (instead of two parallels), and *k* will have the value 2·2. The value of *k* for various widths of poles and breadths of coils has been calculated by Kapp, with following results:—

Pole width.	Total breadth of Copper in Coil.	*k*
1. Equal to pitch	Equal to pitch (covering whole surface)	1·160
2. Equal to pitch	Half of pitch (covering half surface)	1·635
3. Half of pitch	Equal to pitch (covering whole surface)	1·635
4. Half of pitch	Half of pitch (covering half surface)	2·300
5. Third of pitch	Third of pitch (covering third of surface)	2·830

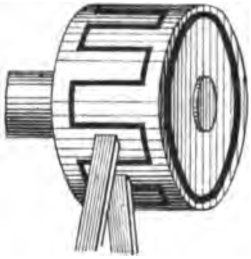
If there were no spreading of the magnetic field, No. 4 of these would be best (being also nearest sine-law). The useful breadth of wires is that which would just lie between the pole-tips. The output of a machine having a given thickness of copper in the gap is proportional to the number of such wires to width of the pole-face; therefore to the product of the two breadths, the sum of which, if there were no magnetic spreading, would equal the pitch. Hence the output would be a maximum when the breadth of coils and width of poles were each half the pitch. But Elihu Thomson has found by experiment that, owing to the distortion of the magnetic field when the machine is running, there is an advantage in making the breadth of copper greater than this, that is by diminishing the aperture of the coils to something less than one-half the width of the pole-face.

There has been much controversy whether armatures should or should not have iron cores. Iron cores are certainly inadmissible in thin disk armatures, as they would inevitably jamb against the pole-faces. Owing to the high frequency of alternation, the loss by hysteresis in machines with iron cores becomes serious, unless the magnetization is kept down below 7000 lines per sq. cm., and even then is not negligible. On the other hand, there is more loss by eddy currents[1] in the copper in machines not having iron cores.

MODES OF EXCITATION OF FIELD-MAGNETS.

In the older machines the field-magnets were either of steel permanently magnetized, or else electromagnets separately excited. About 1869 began the practice of making these machines self-exciting by the method of diverting a small current from one or more of the armature coils, which were for this purpose separated from the rest, this current being passed through a commutator, which rectified the alternations and made it suitable for magnetizing the field-magnets. Such commutators were used by Wilde and by Holmes, and have in general the form depicted in Fig. 419, consisting of two metal cylinders cut like crown-wheels, having the teeth of one projecting between the teeth of the other. They are insulated from one another, one being connected to one end of the wire of the armature coils that are to be used for exciting, whilst the other is connected to the other end of that wire. Two brushes are set so that one presses against a tooth of one, whilst the other presses against a tooth of the other part. Such commutators had previously been used in small motors.[2] Holmes used a system of parallel bars (like the Gramme collector) connected together alternately into two sets. If the field-magnets are wound with fine wire, such a commutator may be used to rectify a fraction of the current from the whole of the armature coils, thus making the machine virtually a self-exciting machine. It is, however, more usual to supply each alternator with a small auxiliary continuous-current dynamo, termed its *exciter*.

FIG. 419.



COMMUTATOR FOR SELF-EXCITING ALTERNATORS.

A convenient way of regulating the current or potential of alternators is to interpose a variable resistance in the exciting circuit; the resistance being operated by hand or by some automatic regulator (see Chapter XXVII.). This method is applicable either to separately excited or to self-exciting machines. In the case where separate exciters are used, the performance of the alternator may be regulated by controlling (by variable resistances, &c.) the exciting circuit of the exciter.

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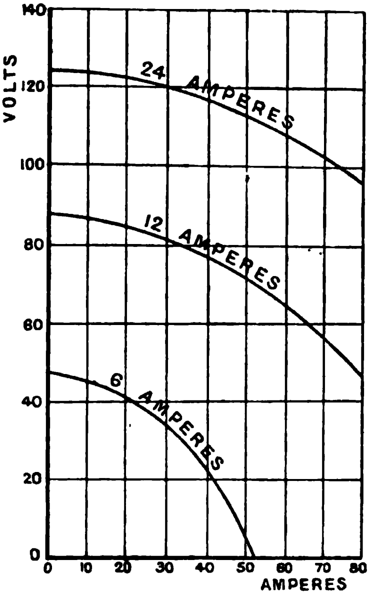
[1] See remarks by Elihu Thomson in comment on Kapp's paper, *loc. cit.*

[2] See Joule, in Sturgeon's *Annals of Electricity*, ii. 122, 1838.

Alternators, when intended for supplying glow-lamps at constant pressure, whether direct at low voltage, or by transformers at high voltage, are usually constructed with such low resistance in the armature part, and with so low a coefficient of self-induction, that they would be almost self-regulating if it were not for the demagnetizing influence of the armature currents. This may be considerable, and is an effect closely akin to self-induction. For supplying lamps in series with a constant current a somewhat different type of alternator is needed, having considerable self-induction in the armature. This is attained by winding the armature coils, not on the outside of the core, but deeply embedded in it, or wound on long core-plates to give considerable magnetic inertia.

FIG. 420.



The demagnetizing influence of the armature current has been studied by Esson,[1] who has determined (Fig. 420) the external characteristic of an alternator when separately excited with different amounts of current. The three curves correspond to the three cases when the separate exciting current measured respectively 24, 12, and 6 amperes. The effect of the armature current is most marked when the field-magnets are weakly excited, and apparently roughly in proportion to the square of the armature current. In the Mordey alternator (p. 273) the field-magnet is so powerful that the diminution of the electromotive-force from this cause with the full current is less than 3 per cent. of the whole, the resulting droop in the characteristic being extremely slight. Swinburne[1] has also discussed armature reactions.

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[1] See *Electrical Review*, xviii. p. 248, March 1886.

Some load-curves for an alternator have been given by Kapp (*loc. cit.*), and should be compared with Fig. 287, p. 435.

Esson finds that the output of alternators may be expressed in terms of the armature dimensions and speed as follows :—

$$\text{Output (watts)} = 0\cdot0296\, d^2 \mathrm{L}\, n,$$

where d is diameter and L length, in centimetres, and n the number of revolutions per second. This is about 40 per cent. of the output of a direct-current dynamo of equal dimensions.

EXAMPLES OF ALTERNATORS.

Kapp's Alternator.—A modern alternator with ring-armature is that of Mr. Gisbert Kapp. This pattern has been constructed by the Oerlikon Machine Works, by Messrs. Goolden, and by Messrs. Johnson and Phillips. It differs from most other alternators in having double magnetic circuits. The machine depicted is a 30-kilowatt machine, having an output of 15 amperes at 2000 volts, at 700 revolutions per minute. The field-magnet consists of two crowns, of 12 poles each, alternately N and S, but each N-pole in one crown is opposite a N-pole of the other crown; so that the magnetic lines entering the ring from both faces stream laterally through the core. The armature core consists of annealed strip iron 2·5 inches (= 6·35 cm.) wide, and 0·025 inch (= 0·063 cm.) thick, which is wound up, with paper between, upon a strong foundation-ring of cast iron 28 inches (= 71·1 cm.) in diameter. The radial depth of the core is 8 inches

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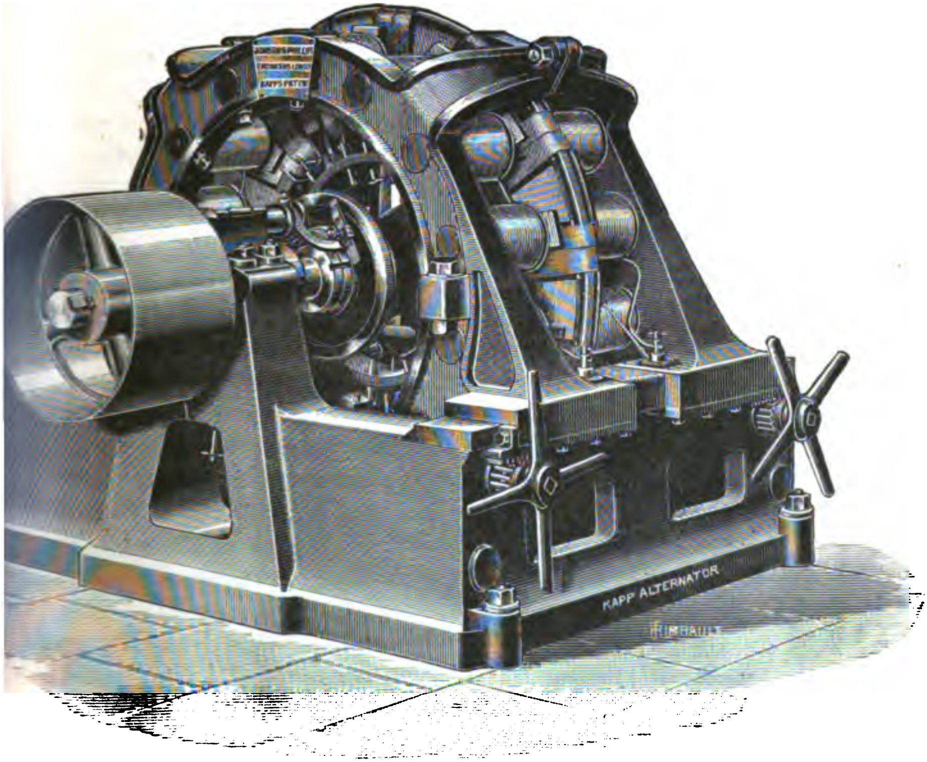
[1] *Journal Inst. Electrical Engineers*, xx. 173, 1891.

(= 20·3 cm.) and the actual cross-section of iron in it 16 square inches (= 103·2 sq. cm.). Driving-horns of ebonite are inserted at intervals, and the coils are separated from the core-iron by a liberal use of mica and paper, and are prevented from cutting at the outer edge by the insertion of a rounded rim of mahogany. On the ring are wound twelve coils, each of a breadth a trifle less than half the pitch, and of about 100 turns each, the total number being 1190 turns. The ends are strained down through insulating bushes that pass through eyes in the foundation-ring, and are joined up to put the whole 1190 turns in series. The resistance (warm) is 7 ohms.

FIG. 421.



KAPP'S ALTERNATOR.

The 24 magnet-cores of wrought iron are each 3¾ inches diameter, having a sectional area of 11·04 square inches. They are provided with polar expansions of nearly rectangular form, about 7¼ inches by 4 inches, giving polar area of 29 square inches. The depth of polar gap from iron to iron is about 0·5 inch. The yoke-rings are of cast iron.

As self-induction in such a ring is considerable, preliminary experiments were needed to show what allowance must be made for this in the excitation. When run on short circuit, and with field-magnets separately excited to a degree that would have given the armature an electromotive-force of 1540 volts on open circuit, the armature current was 25 amperes. Hence it was concluded that when the armature current is 15 amperes, there will be a self-induced electromotive-force of 925 volts. Hence, as these will be in quadrature with the effective volts (which are desired to be about 2100), we may suppose that at the machine's full load the impressed electromotive-force will have to be

$$\sqrt{925^2 + 2100^2} = 2295.$$

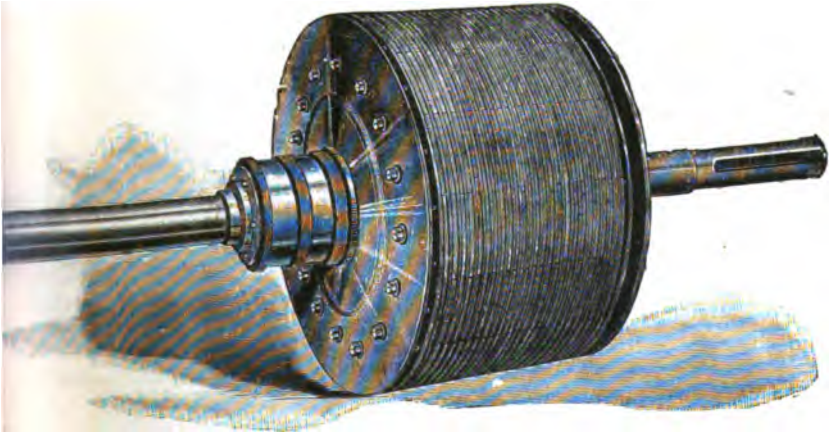
Applying the formula, p. 650, and assuming $k = 2{\cdot}3$, we get $N = 1{,}250{,}000$ as the number that must be cut at each of the 12 poles, or 625,000 to flow through each of the 24 polar faces. This makes $B_{''} = 39{,}120$ in the armature core, and 57,000 in the magnet core. To produce this magnetization an exciting current of about 8·7 amperes is required in the field-magnet coils, the total resistance of which is about 11·2 ohms (warm). Hence the power wasted in the field-magnet is about 850 watts, or 2·83 per cent. of total output.

In Plate XXII. are given drawings of another Kapp alternator, built at the Oerlikon Works. This is an 80 HP. machine, running at 600 revolutions per minute, yielding 30 amperes at 2000 (virtual) volts, and weighing 3½ tons. Upon the same bed-plate is mounted an exciter. The field-magnet consists of two crowns, of 14 cylindrical wrought-iron magnets each, with rectangular pole-pieces. In each field-coil there are 186 turns, with total resistance 1·76 ohm.

taking 21 amperes to excite fully. The ring has upon it 14 coils of treble cotton-covered wire, 0·120 inch in diameter, 80 turns each in two layers: total resistance 1·8 ohm.

For the Metropolitan Supply Company Mr. Kapp has designed some larger machines, giving 60 amperes at 2000 volts, at 600 revolutions per minute. The following are particulars of these machines:—Number of poles, 20. Frequency = 100 ∿. Armature: foundation-ring, 42 inches diameter; core, 2¾ inches wide by 9 inches deep; winding 20 coils each 40 turns of copper tape, united in one series, $r_a = 0·926$; or if joined in two series, $r_a = 0·2317$, and output is then 120 amperes at 1000 volts. Field-magnet cores, 8½ inches long, 4½ inches diameter; pole-shoes, 8 inches by 3¼ inches; coils, 144 turns each; total resistance, 2·26 ohm; and carry exciting current 22 amperes to 25 amperes at full load.

FIG. 422.



ARMATURE OF WESTINGHOUSE ALTERNATOR.

Westinghouse (Stanley's) Alternator.—A drum armature is employed in the alternator[1] of the Westinghouse Company depicted in Fig. 422.

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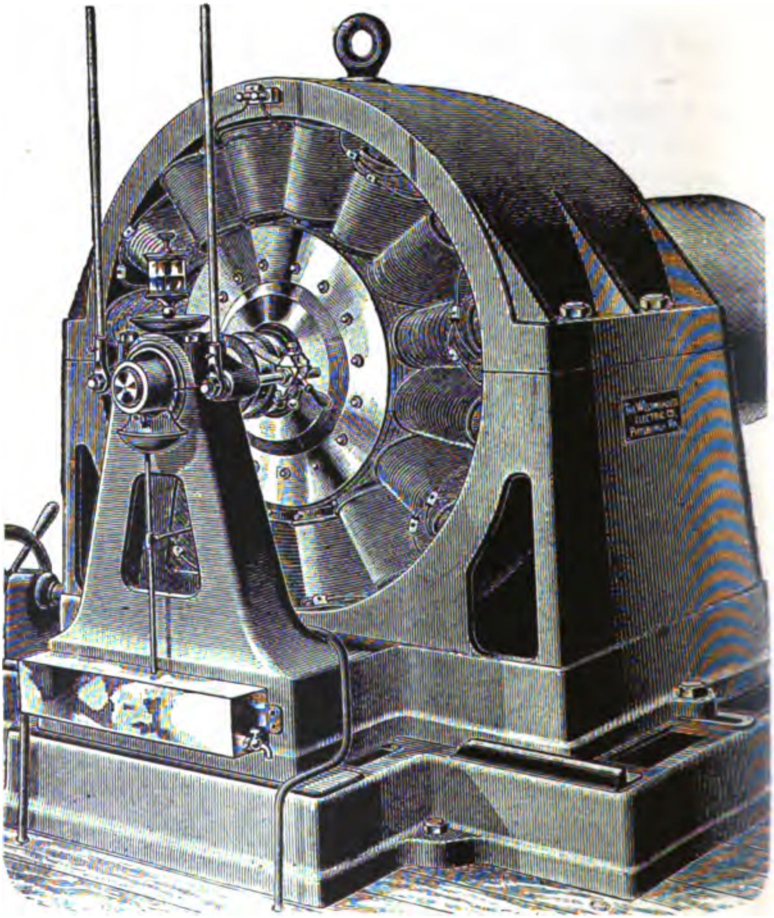
[1] For further information and tests see *Electrical World*, vol. xi., Sept. 3, 1887; vol. xv. 242, 1890; *Electrician*, xxv. 603 and 706, 1890; *Electrical Review*, xxv. 233, 1889; British Specifications of Patents, 9725, 9726, and 9727 of 1887; *La Lumière Électrique*, xxv. 643, 1887; xxvii. 8, 1888.

In the 150 kilowatt machine there are 16 radial poles pointing inwards and fixed externally to a common cylindrical cast-iron yoke. The armature core, which is 23 inches in diameter and 12 inches in length, is built up of thin iron disks, with holes perforated for ventilation. The winding consists of 16 coils, wound in flat hanks on special formers,

FIG. 423.



WESTINGHOUSE ALTERNATOR.

and then laid side by side upon the periphery of the core, not overlapping, and secured by well-insulated binding wires; the ends of the hanks being bent over and secured against the flanks of the drum. The grouping is in two series of eight coils each. The binding wires cover nearly the entire surface (see Fig. 422). This machine weighs three tons, and gives 145 amperes at 1100 volts at 1080 revolutions per minute. The journals are very long and are carried through spherical-seated bearings. To permit of repairs the upper half of the field-magnet can be lifted off. The exciting current is from 25 to 30 amperes at 100 volts. The number of alternations is 8640 per minute or 144 per second. In the most recent Westinghouse machines the armature coils are wound on toothed core-disks.

Elihu Thomson's Alternator.—This machine closely resembles the Westinghouse, but differs in important details. The armature coils, which are wound with square wire, cover a large amount of surface, and are not turned down in flaps over the ends of the drum. The field-magnets have from eight poles in small machines to 22 poles in the largest. In the small machines all the armature coils are united in one series as in Fig. 416; in the larger sizes they are in two series. Three types of these alternators are used. Some are separately excited: others are made self-exciting by the device of winding a few turns of wire in drum fashion around the core in the inter-spaces of the main coils, the end being brought out to a commutator on the shaft; others are called "composite," from the circumstance that the field-magnets are partly separately-excited and partly self-excited from the main current of the machine, which for this purpose is carried through a shunted commutator. It is this third class of machine which is depicted in Fig. 424. An exciter furnishes current to eight of the ten field-magnet poles, the excitation being controlled either by a variable resistance R_1 in the shunt circuit, or by R_2 in the exciting circuit. The other two field-coils are connected to brushes on a rectifying commutator C, shunted by the resistance R_3. The main current on its way to or from the contact-rings A B must pass through this commutator or the shunt R_3. Hence the excitation will

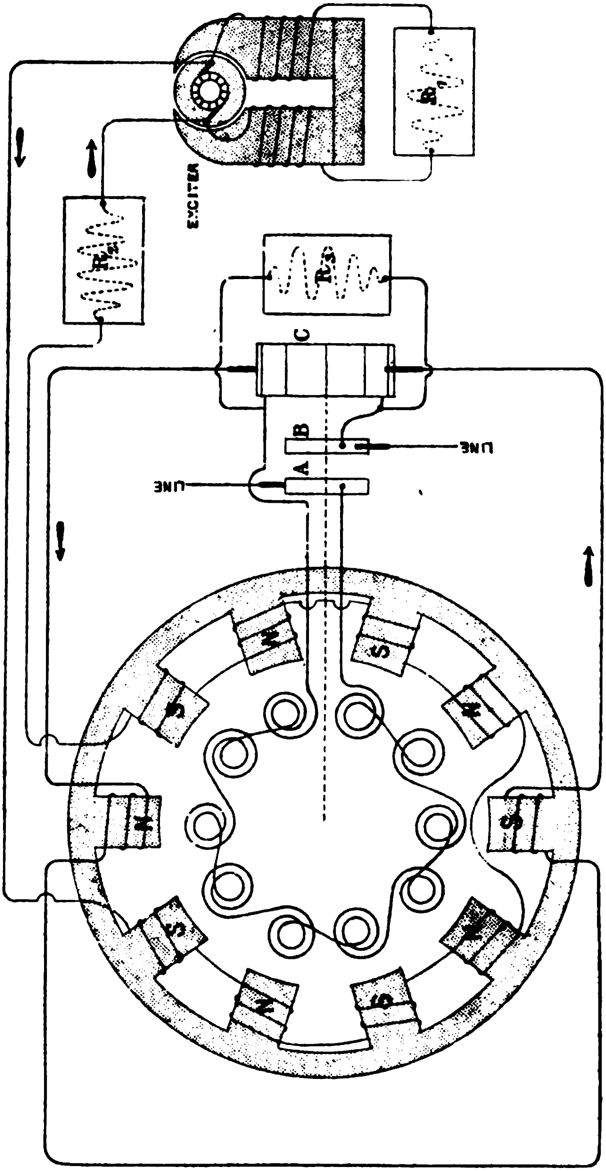


FIG. 424.

ELIHU THOMSON'S ALTERNATOR: COMPOSITE METHOD OF EXCITATION.

be of two parts, an initial and constant part, and a variable part depending on and proportional to the main output of current. Hence this arrangement has the same virtues as the compound-winding of direct-current dynamos. The resistance R_3 which is of German silver attached to the frame of the machine, permits the amount of compensating excitation to be varied in different machines, so that the same size of machine can be used to compensate for the fall of potential over various lengths of line. This type of alternator is made in three sizes, giving respectively 35, 70, and 140 amperes at 1000 volts, at speeds from 1500 to 680 revolutions per minute.[1]

Prof. Elihu Thomson has devised another form of alternator, described on p. 686.

Blakey-Emmott Alternator.—This machine, depicted on Plate IX. and Plate XXIII., is of the same general type as the preceding; but whereas the windings of the two preceding sorts are lap-windings, that of the present machine is a wave-winding resembling Fig. 203, p. 314.

The armature core is built up of very thin charcoal iron disks mounted on a gun-metal spider keyed to the driving shaft. The winding consists of bands of copper wires, the breadth of the bands being equal to the width of the poles. These bands are laid in a sinuous form upon the surface of the armature, the bends being laid upon the end plates. The final ends are carried to substantial rings of copper serving as collectors. Carbon block brushes are used and are found very satisfactory. The bearings are self-centering. The sketch in Plate XXIII. represents the 15A size, which gives an output of 7·5 amperes at 2000 volts, or 15,000 watts at a speed of 1200 revolutions per minute. The number of poles is ten, and the frequency therefore 100 complete periods per second. The diameter of the armature core is 18 inches, and the length 8½ inches. The total number of active conductors in the armature is 1140, the weight of copper being 13·3 lb. The resistance is 4·48 ohms; and, when run on open circuit with full exitation, the volts generated are 2050. The weight of copper on the field-magnets is 150 lb. The curve of induction of this machine is given on p. 619. The armature can be readily examined in position by removing the top half of the field-magnets. These machines are made by Messrs. Blakey, Emmott, & Co., of Halifax, in seven sizes, with outputs varying from 12,000 to 120,000 watts.

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[1] See *Electrical World*, xiii. 19, 1889; xiv. 197, 1889; and *Electrician*, xxvi. 133, 1890.

Phœnix Alternator.—This machine is constructed by Messrs. Paterson and Cooper, from the designs of Mr. Esson;[1] and has a general resemblance to those described, being multipolar with twelve poles. The magnet cores are of wrought-iron made narrow to receive the coils, and widening into a polar face nearly of double area. They are carried on a cast-iron yoke ring; and the width of the pole-faces is half the pitch. Had the cores been of equal width all the way along they might nearly as well have been of cast iron; but with wrought iron of high permeability, the saving in copper more than pays for the cost of tooling. The armature is built up of core rings with internal and external diameters in the ratio of about 7 to 5, over which are laid six flat coils each equal in breadth to three times the width of the magnet cores, and laid on the periphery with spaces equal to the width of the core between them.

Hopkinson Alternator.—This machine has multipolar magnets, with a width of pole face exceeding three-fourths of the pitch. The armature wires are not laid on the outside of a drum, but are coiled upon short polar projections of laminated iron. The machine shown runs at 800 revolutions per minute, giving 30 amperes at 1000 volts. The armature resistance is 0·55 ohm, and that of the magnet coils 2 ohms. The exciting current is 21 amperes. An electrical efficiency of 95 per cent. is claimed for the machine. Its exciter, a small "Manchester" dynamo, is mounted on a bracket to run on the same shaft. These machines (Fig. 425) are built by Messrs. Mather and Platt.

Ganz-Zipernowsky Alternators.—Various forms have been built[2] by Ganz & Co., of Buda-Pesth, chiefly from the designs of M. Zipernowsky. The general principle of these machines has already been described on p. 644; but some have been otherwise constructed. A very large machine was shown at Vienna, by Messrs. Ganz, in 1883. It was capable of furnishing light for 1200 Swan lamps (20 candle-power each). The thirty-six bobbins of the field-magnet were set concentrically on an iron frame, and rotated within an outer circle of thirty-six armature bobbins. The field-magnet coils were, in fact, the fly-wheel of the high-pressure compound

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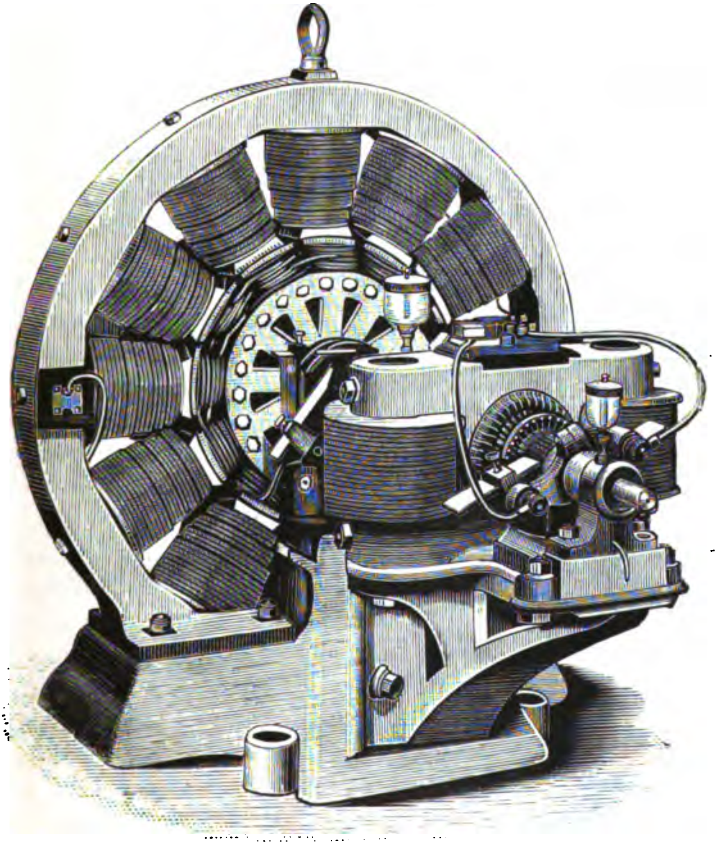
[1] *Journal Institution Electrical Engineers*, xx. 289, 1891.

[2] See *Centralblatt für Elektrotechnik*, xii. 554, 1889; also *Electrical Review*, xv. 70, 1884; xvii. 115, 1885; *Electrician*, xxv. 258, 1890; *Electrical World*, xiii. 297, 1889; xvi. 73, 1890; *La Lumière Électrique*, xxxi. 121; and xxxii. 159 and 582, 1889.

FIG. 425.



HOPKINSON ALTERNATOR.

engine which drove the dynamo and its exciter. The diameter of the rotating part was 2½ metres. A salient feature of this machine was the fact that any one of the coils, either of armature or field-magnets, could be removed from the side of the machine in case such were needed. The whole fly-wheel could, in this way, be taken down by one man in a few minutes. The armature coils were attached flat against the inner periphery of a large ring of iron wire ; there being no cores protruding through the armature coils. At Frankfort, in 1891, a large Ganz alternator was shown by the Helios Co.,[1] of a capacity of 400 kilowatts, giving 200 amperes at 2000 volts at 125 revolutions per minute. The armature consisted of 40 T-shaped punchings, like Fig. 410, surrounded with coils each working at 100 volts, the whole being coupled up in two series of 20 each. The rotating field-magnet is 299·2 centimetres in diameter, and 38 centimetres wide. The electrical efficiency is given at 95·6, and the nett efficiency at 91·5 per cent. Four very fine examples of the Ganz alternator exist in the central station of Rome,[2] each being of 320 kilowatts capacity, driven direct at 125 revolutions per minute by separate compound engines of 500 HP. each. They have rotating field-magnets with 40 radiating poles of solid iron, the diameter being over 9 feet. The interior diameter of the armature ring frame is about 9½ feet, the core being built up of sheet iron and paper as described. There are 40 coils, each generating 50 volts, all united in series, and capable of carrying 200 amperes, the wire being 6 mm. in diameter. The bobbins of the field-magnet coils are wound on rectangular split-zinc formers about 15 inches high and 20 inches wide, the windings being more numerous toward the outer end. The armature windings, 30 in each coil, are contained on vulcanized fibre frames 19 inches long, 10 inches wide, and 2 inches deep, and are clamped in place by skeleton bronze frames.

Siemens Alternators.—Messrs. Siemens and Halske were early in the field in 1878 with alternators designed by von Hefner Alteneck ; having a disk armature (see Fig. 412), in which the coils are wound usually without iron, upon wooden cores. Copper ribbons insulated from one another by strips of vulcanized fibre are used for the coils; the connexions being made by soldering the strips with silver solder. In some forms of the machine, the individual coils are enclosed between perforated disks of thin German silver. When currents of great strength are required, but not of great electromotive-force, the coils are coupled up in parallel instead of being united in series. In Fig. 426 a small continuous-current machine of vertical pattern, such as was described on p. 193, is shown in action as an exciting machine

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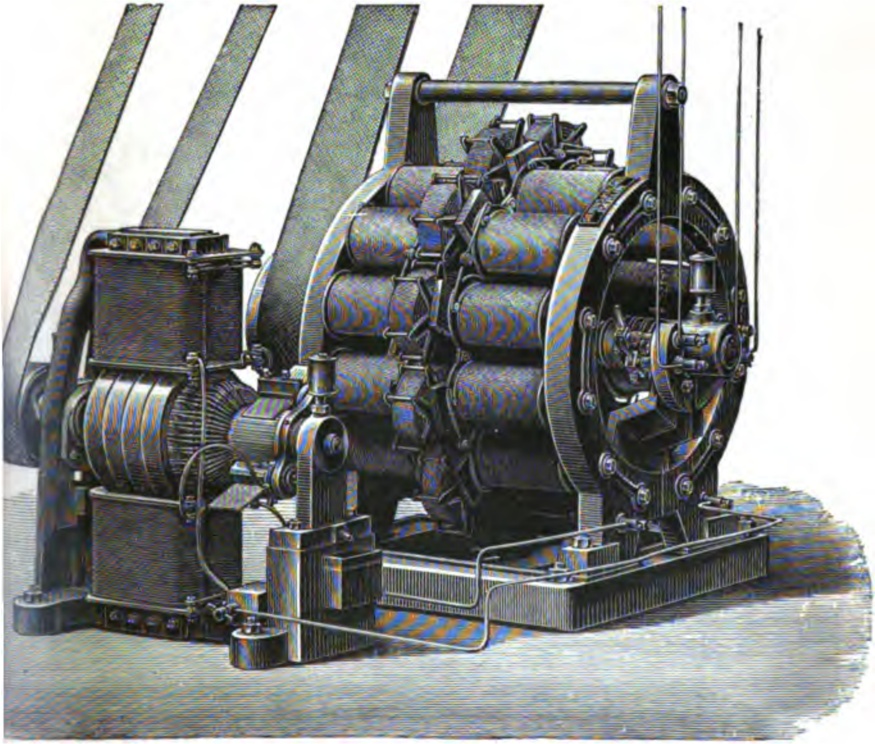
[1] See description by Mr. Esson, and cut, *Electrical Review*, xxix. 503, 1891.

[2] See description by Prof. Fleming in the *Electrician*, xxv. 317, 1890.

FIG. 426.

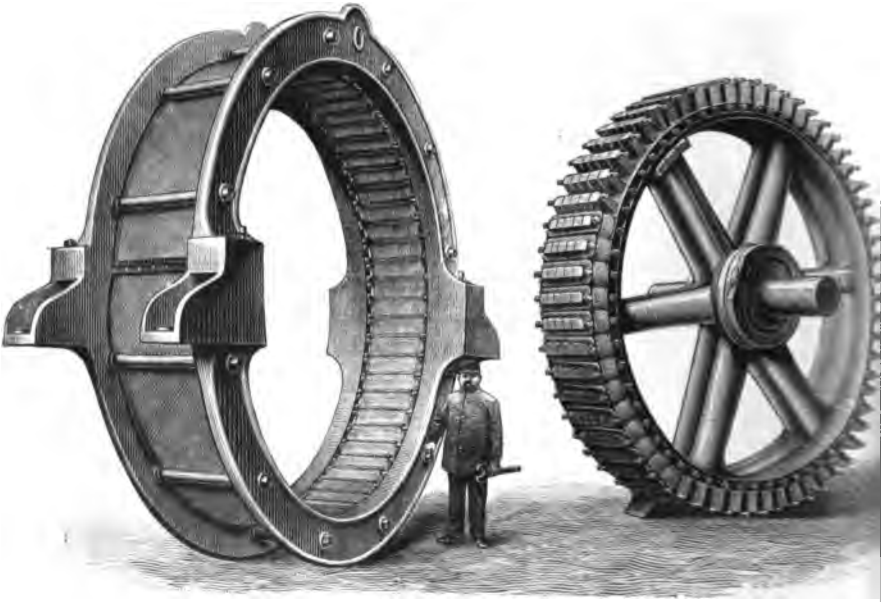


SIEMENS ALTERNATOR, WITH ITS EXCITER.

to furnish the magnetizing currents to the stationary field-magnets of the alternator.

More recently Messrs. Siemens and Halske have returned to a pattern more nearly resembling Lontin's design, with a multipolar rotating field-magnet and fixed external armature. The large 330 kilowatt machine shown at Frankfort in 1891 is depicted in Fig. 427. The field-magnet consists of 60 bobbins with

FIG. 427.



SIEMENS AND HALSKE ALTERNATOR.

laminated cores built upon the rim of a fly-wheel, 3·7 metres in diameter over all; whilst the armature ring is 4·6 metres (14 ft. 9 in.) in external diameter. When running at 100 revolutions per minute, it yields 165 amperes at 2000 volts. The construction of the armature is as follows:—A laminated ring of 60 segments, each built up of straight iron plates stamped with end-projections, is held together firmly in a cast-iron frame. Each segment before being put in place is wound with 20 turns of a conductor made of stranded copper wire compressed to a square section, each wire in the strand being lightly insulated with a coat of enamel. The ring thus formed is 4·6 metres in diameter, and 50 centimetres in width parallel to the axis; the end projections of the core-plates constituting 60 internal teeth. It is therefore simply a laminated Pacinotti ring with sections coiled alternately right and left-handedly. Any one of the sections can be removed singly for repair. The laminated magnet-cores carry 56 windings each, and receive a current of 56 amperes at 70 volts for excitation.

Gordon's Alternator.—Gordon's alternator was described and figured in the earlier editions of this book. It has twice as many coils in the fixed armatures as in the rotating magnets, there being 32 on each side of the rotating disk, or, in all, 64 moving coils; while there are 64 on each of the fixed circles, or 128 stationary coils in all. The latter are of an elongated shape, wound upon a bit of iron boiler-plate, bent up to an acute V form, with cheeks of perforated German silver as flanges.[1] The result of thus arranging the coils in two sets is that there are two distinct currents differing in phase by a quarter period. The armature parts of the machines used at Paddington have lately been reconstructed and laminated more thoroughly, to obviate the waste by eddy-currents, which was serious in the machines as first designed.

Elwell-Parker Alternator.—This machine, built by the Electric Construction Corporation, Wolverhampton, is shown in Plate XXIV. The field-magnets, which are internal and revolve, present a set of radiating poles, built upon a foundation ring of mild steel, into which the magnet-cores of soft wrought iron are securely bolted by T-shaped pieces, the head of each, which forms a pole-piece, grooved on its surface, and the shank of which passes through the core and foundation ring. The armature-core consists of an external assemblage of segmental core-rings bolted between two end frames of cast iron. The armature coils, which are separately wound of copper tape on wooden cores, are secured by wooden clamps and iron bolts against the inner periphery of the core-rings. The external breadth of each armature coil is equal to the pitch, and the internal breadth is slightly less than the width of the pole-face.

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[1] For further details of the Gordon dynamo, see Mr. Gordon's *Practical Treatise on Electric Lighting* (1884), p. 162.

The following are particulars of two recent Elwell-Parker alternators of 30 and 50 kilowatts respectively:—

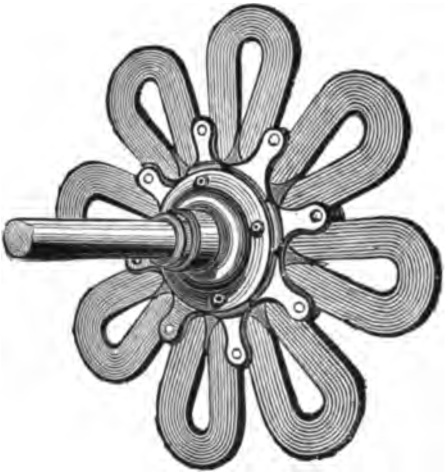
Output (watts)	30000	50000
Amperes	30	25
Volts	1000	2000
Frequency (periods per second)	60	83·3
Revolutions per minute	600	500
Number of poles	12	20
Diameter of F.M. circle	36″	$45\frac{5}{16}''$
Length of magnet cores	$6\frac{3}{4}''$	$8\frac{5}{8}''$
Section of magnet core:—Width	3″	2″
Breadth	6″	10″
Pole-faces:—Width	$4\frac{1}{2}''$	$3\frac{1}{2}''$
Breadth	6″	10″
Turns on each F.M. pole	267	344
Exciting current	16 to 18	11·6 to 12·3
Resistance of magnet coils (ohms)	3·26	9·5
Clearance from poles to coils of armature ..	$\frac{1}{8}''$	$\frac{1}{8}''$
Total clearance poles to core-rings	$\frac{1}{2}''$	$\frac{15}{32}''$
Armature core, internal diameter	37″	$46\frac{1}{4}''$
,, ,, external ,, ...	45″	$56\frac{1}{4}''$
,, ,, external breadth	$6\frac{1}{4}''$	$10\frac{1}{4}''$
Armature coils, number of	12	20
Aperture in coil, length of	8″	$12\frac{3}{8}''$
,, ,, breadth of	$4\frac{1}{2}''$	$3\frac{1}{2}''$
External breadth of coil	$9\frac{5}{8}''$	$7\frac{3}{16}''$
Turns in each coil	34	28
Width of copper ribbon	0·25″	0·25″
Thickness of copper ribbon	3·060″	0·049″
Total weight (lbs.) of copper on armature ..	60	115

Plate XXV. depicts the Elwell-Parker alternators as used in the central station at Manchester Square, London, each coupled direct to a triple-expansion high-speed Willans engine.

Ferranti's Alternators.—This machine, as brought out in 1882, was based on the joint but independent proposal of Sir W. Thomson and Mr. S. Z. de Ferranti to substitute wave-windings for coils.

Sir W. Thomson proposed originally that the armature should consist of copper strips wound in a star fashion between projecting teeth on a wooden wheel. He also proposed to use as field-magnets a form of electromagnet in which the

FIG. 428.



FERRANTI ARMATURE (1882).

FIG. 429.

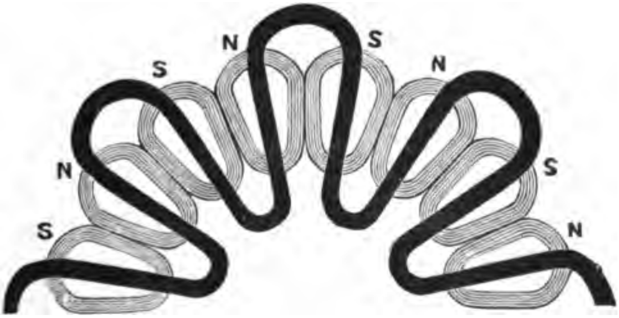


DIAGRAM OF (OLD) FERRANTI ALTERNATOR.

wires that bring the exciting current pass up and down, in a zigzag form, between iron blocks projecting from an iron frame. In the machine as constructed at that date,[1] the field-magnet consisted of two crowns of alternate poles, precisely as in the alternators of Wilde and Siemens; and the armature consisted of strip copper bent into a wavy star form. There were eight loops in the zigzag (as shown in Fig. 429, which depicts half only of the arrangement), and on each side were sixteen magnet poles; so that the moving parts were twice the angular breadth of the fixed parts. The copper strip was wound round on itself (with insulation between) in many layers; the limbs of the star being held in place by insulated bolts passing through star-shaped face-plates of brass. The advantage of the armature of zigzag copper was supposed to lie in its strength and simplicity of construction.

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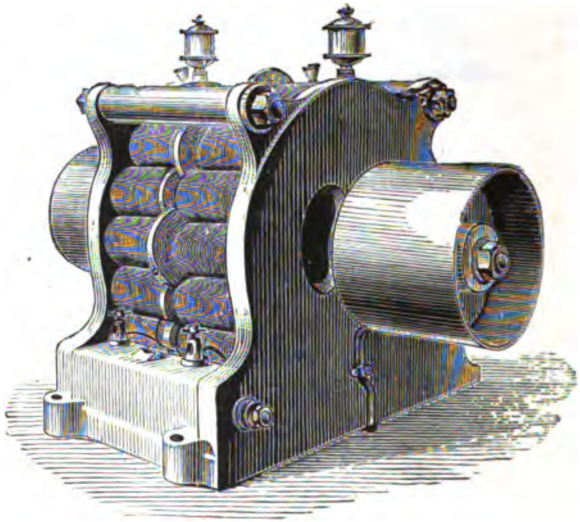
[1] See Specification of Patent, No. 3702 of 1883; and, for later details, No. 702 of 1887.

FIG. 430.

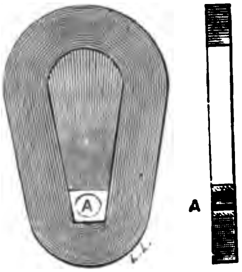


FERRANTI-THOMSON DYNAMO.

The framework of the field-magnet was cast in two halves, which were held together by bolts.

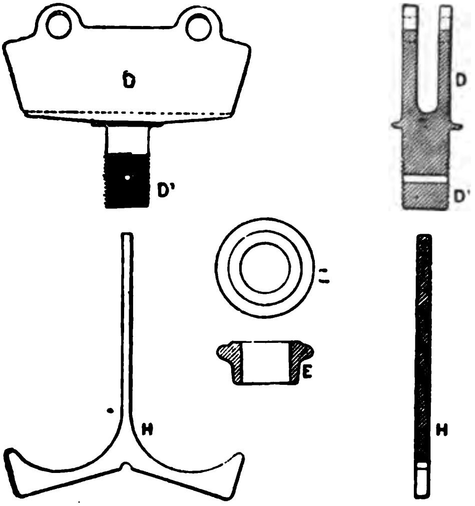
In the later alternators of Ferranti the zigzag mode of winding has been entirely abandoned, and the coils are wound separately and then assembled into a disk. The mode of construction is explained by the figures which follow, and by those on Plate XXVI. Each coil is wound upon a rigid core. The cores are constructed of brass strips spreading fan-wise, with asbestos between, brazed solidly together at one end, and to a brass piece which is drilled with an aperture A (Fig. 431). The winding, the inner end of which is soldered to the brass piece, is of ribbon copper slightly corrugated to secure greater rigidity, wound with a tape of thin vulcanized fibre between. The coils are mounted in twos in brass coil-holders, depicted at D, Fig. 432, into which, with interposed layers of mica and fibre, they are secured by bolts which pass through their eyes. The two coils in each holder are separated mechanically and electrically by interposing a piece of fibre of the form shown at H; but the holder constitutes a metallic connection from the eye A of the one to the eye A of the other. Consequently, a current circulating from outside to inside of one coil must

FIG. 431.



SINGLE COIL OF FERRANTI ARMATURE.

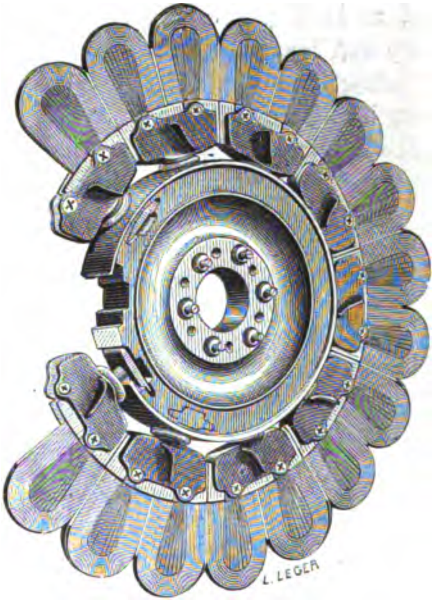
FIG. 432.



DETAILS OF FERRANTI ARMATURE.

circulate from inside to outside of the other. The outside end of each coil is joined to the outside of the nearest coil in the next holder. The holders must of course be insulated, and yet held mechanically and firmly. For this purpose they are provided with a tail-piece D′, of circular section, which passes through a porcelain bush E, and is threaded to receive a metal foot which is further secured by a pin passing through D′. The tail-piece, protected by its porcelain bush, passes through the rim of a strong foundation ring, having apertures into which the metal feet are inserted, but which are much wider than them. The gap between them is then filled up by pouring in a molten compound of sulphur and powdered glass, which secures and insulates them. On the side of each coil-holder projects a small oblique wing, to promote ventilation. In all the larger machines the coils are connected up, as shown in Fig. 433, in two series, which

FIG. 433.

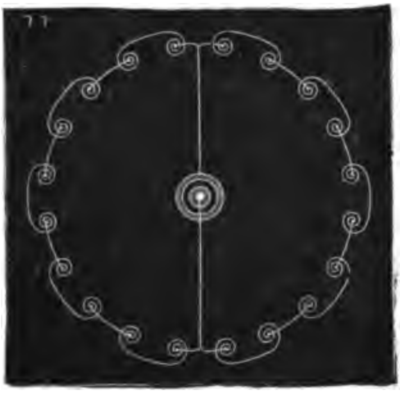


FERRANTI ARMATURE, SHOWING MODE OF MOUNTING COILS AND COIL-HOLDERS.

are joined together in parallel. This grouping is effected by placing all the coils in one half circumference right-handedly, and in the other left-handedly.

Two copper rods pass inwards from the tail-pieces of two of the coil-holders at opposite ends of a diameter, and are led to the collectors.

FIG 434.

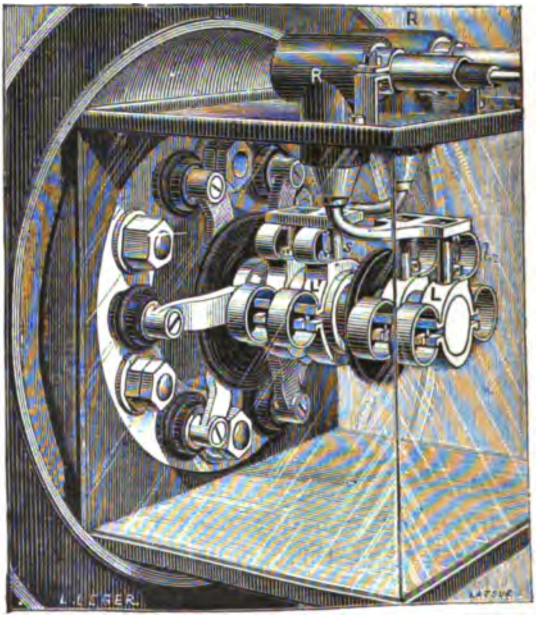


CONNEXIONS OF FERRANTI ARMATURE.

The collecting arrangements are separately shown in Fig. 435, and are mounted on the end of the shaft. One connexion from the armature coils communicates with a structure consisting of three arms at 120° apart. These passing out through ebonite bushes unite to a copper cylinder, which passes through a large ebonite bobbin provided with deep flanges at back and front. Upon the front end of this cylinder two collectors press, each collector consisting of two half-rings L of copper united by C-shaped springs. These two collectors are united by a curved connector to the insulated junction-piece R going to the circuit. The other connexion from the armature coils is united by three other arms to a copper mantle outside the ebonite bobbin, and on this mantle press two other collectors L′, similar to, but slightly larger than the former pair. These communicate with the other pole of the circuit.

In Plate XXVI. are depicted two forms of Ferranti's alternators. Fig. 1 relates to a 300 horse-power machine, and gives a view of half the armature and half the field-magnet. Here it is seen how the copper connector D^2 passes from the coil-holder D to m_1, a bolt uniting it to one of the three arms of the collecting apparatus. The cut also shows how the field-magnet is built in two separate halves, each of which can be racked laterally aside by a lever N and rack M to expose the armature for cleaning or repairs. The speed of this machine is 350 revolutions per minute, and the diameter of the armature 5 feet 6 inches.

FIG. 435.



COLLECTORS OF FERRANTI'S ALTERNATOR.

Figs. 2 and 3 of Plate XXVI. represent on a scale of $\frac{1}{50}$ the 1250 horse-power alternator as used at the Deptford lighting-station. These machines, capable of giving 100 amperes at 10,000 volts, when running at 120 revolutions per minute, are driven by rope-gearing from engines of marine type. The pulley, which has grooves for 27 ropes, is nearly 10 feet in diameter, and over 10 feet long. It is built in two parts N and N_1, united by bolts at *a*, and is keyed to the middle of the shaft between two bearings γ mounted on pedestals which curve inwards at both ends. The journals are of unusual length, and the bearings swivel upon spherical seats. End play is prevented by collars at the outer ends of the shaft. The exact position of the pulley upon the shaft can be adjusted by a central screw collar *c*, turned by a handle U. This adjustment is rendered necessary because the armature is mounted upon the end rim F of the pulley itself, overhanging the bearing; and, as the clearance between the armature-coils and the magnet pole-faces is very small, any wearing of the bearings might cause the armature coils to come dangerously close to the pole-faces. The coil-holders and porcelain bushes are shown at D and E. The magnet-poles are held in a large external cast-iron frame. There are 48 poles in each crown, of alternate polarity. The faces are covered with caps of thin ebonite to protect against spark discharges from the coils. The armature coils, also 48 in number, are each capable of generating about 420 volts, and will carry a current of 50 to 55 amperes without undue heating. The mean diameter of the armature is 15 feet, and its thickness at the working part is only ¾ inch. The peripheral speed is therefore 5850 feet per minute. Owing to the mode of driving the armature, the insulated copper connexions must pass through the bearing, and are therefore carried along in a channel through the shaft. The most elaborate precautions are taken against the possibility of a stoppage arising from over-heating of the bearings. There is a double circulation of water and of oil. On the end of the shaft opposite to the collecting apparatus an eccentric works an oil-pump *p*, which pumps oil through a filter out of the reservoir R under the platform, and distributes it under pressure to the oil-ways *a* in the bearings, whence it returns to the reservoir.

In Plate XXVII., Figs. 1 and 2, are given drawings of the still larger alternator, nearly completed but not yet erected, at Deptford. This machine will furnish 750 amperes at 10,000 volts, furnishing light for 200,000 glow-lamps, and requiring 10,000 horse-power when running at 60 revolutions per minute. The mean diameter of the armature is 45 feet (nearly 15 metres), with a peripheral speed of nearly 8000 feet per minute. The coils, of which there are 48 pairs, are constructed and connected as in the machines previously described, but are carried upon the rim of a large fly-wheel, the rim of which weighs nearly 200 tons. The weight of the completed armature is about 225 tons. The two crowns of field-magnets weigh together with their frames about 450 tons. The armature-wheel is carried upon the middle of a long crank-shaft, having a crank outside the bearings at each end. Right and left stand two compound marine engines, each of 5000 horse-power, which stand about 60 feet high from the ground, and about 80 feet high from the bottom of the magnet-frame, which is sunk below the level of the ground in order to lower the level of the shaft. The collecting arrangements, though not placed at the end of the shaft, are very similar to those of the smaller machines.

Parsons Alternator.[1]—This is a bipolar machine, running at the extraordinary speed of 6000 or even 8500 revolutions per minute; the armature being a plain drum. It is coupled direct to a special high-speed steam turbine by the same inventor.

Mordey's Alternator.—This striking form of machine, first brought out in 1888, is constructed by the Brush Electric Engineering Company, of London. It is depicted in Figs. 436 and 437 and also in Plate XXI. It differs in several essential features from the antecedent forms. Though, as before, there are two crowns of poles between which the armature lies, all the poles on one side are of one kind, north poles, and all those on the other side are south poles. Hence there is no reversal of the magnetic field through the armature coils; the number of magnetic lines through any coil simply varying from zero to maximum and back. As a result of this arrangement, there is a great simplification of the means needed to magnetize the field-magnets. It is no longer necessary to wind a separate magnetizing coil on each protruding pole. One single coil surrounding a central cylinder of iron suffices to magnetize the whole of the poles. There is indeed only one magnetic circuit, branching into separate branches. The construction of the field-magnet, of which a section is given in Plate XXI., and which is separately shown in Fig. 437, is as follows:—

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[1] See *Electrician*, xx. 103, 1887; and *Proc. Inst. Civil Engineers*, xcvii., Feb. 1889.

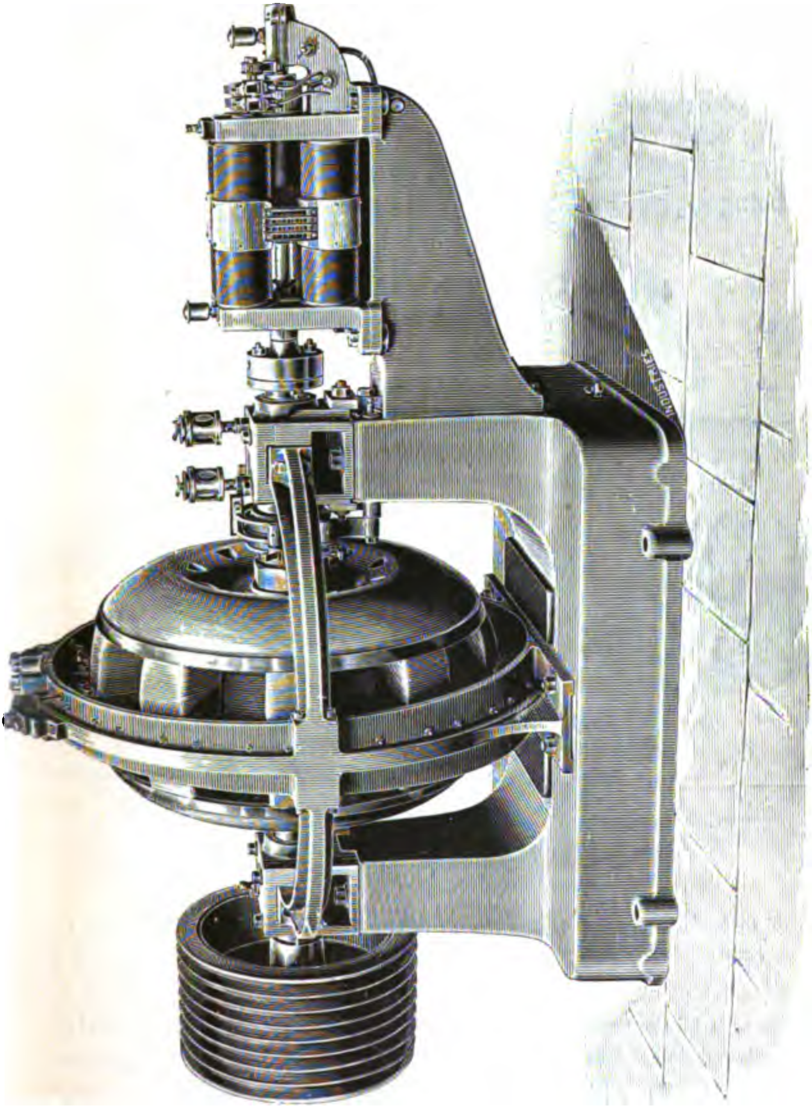
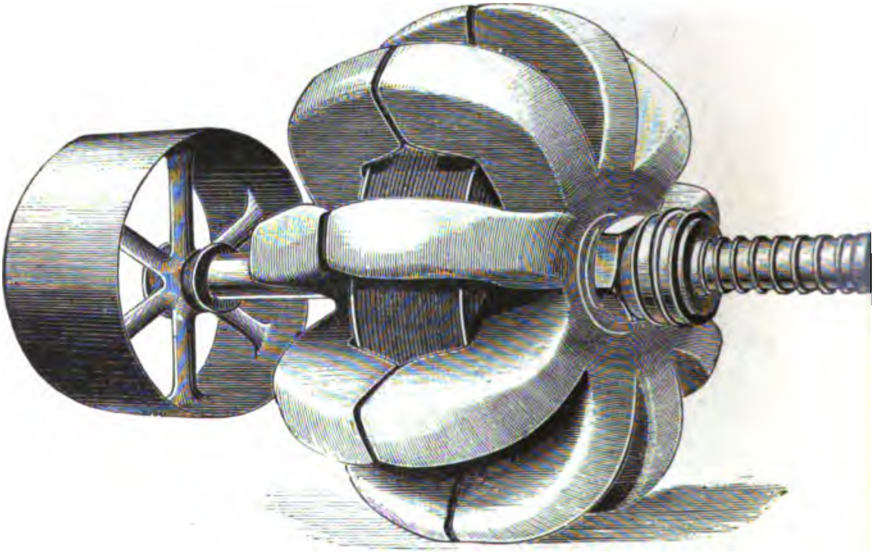


FIG. 436.

MORDEY ALTERNATOR (75 KILOWATT) WITH ITS EXCITER.

A short cylinder of wrought iron, through which the shaft passes, forms the core, and is surrounded by the exciting coil. Against the ends of this core are firmly screwed up the two end castings, each of which is furnished with a number of curved horns (nine in small machines, twelve in larger ones), projecting to within about 17 millimetres, the narrow polar gap being only just wide enough to admit the armature. The entire field-magnet revolves on the shaft, the exciting coil being supplied with current from a separate machine of small size by means of the two contact rings on the shaft on the right in Fig. 437. There is no need for the exciting coil to revolve; but for mechanical reasons it was deemed preferable to wind it actually upon the field-magnet core. The armature (Fig. 438), which stands still, consists, in the smaller machines, of 18 coils of narrow ribbon copper 11 millimeters wide, separated by strips of very thin fibre wound on porcelain cores. The separate coils are clamped at the broad end, by means of German-silver coil-holders lined with mica and fibre and

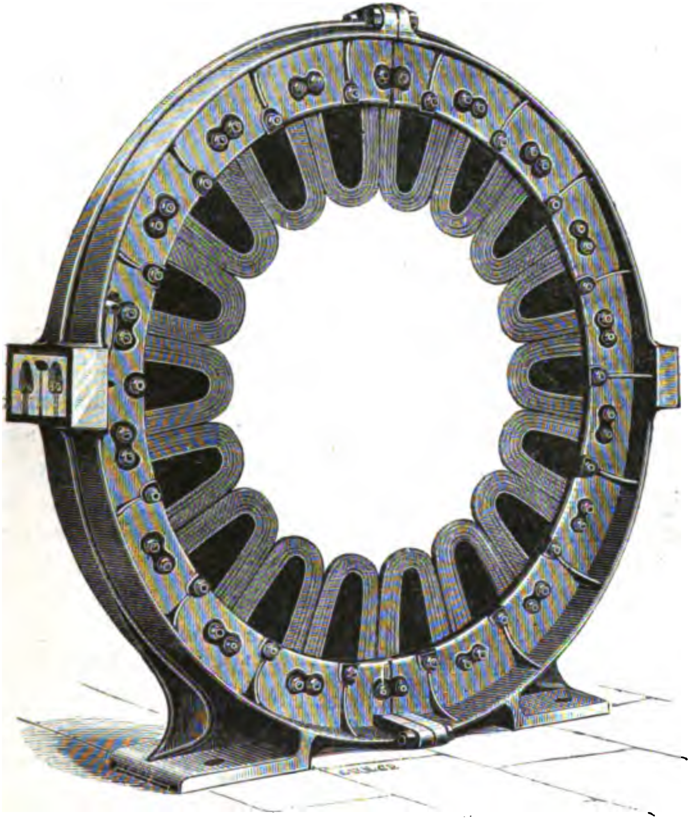
FIG. 437.



FIELD-MAGNET OF MORDEY'S ALTERNATOR.

embedded in ebonite, to a light but firm frame of gun-metal, the ends of the conductors of each coil being brought out through porcelain insulators and suitably connected together. All the metal clampings are outside the magnetic field, and they are so arranged that any one coil can be removed in a few moments without dismounting any other part of the machine. Each of the coils is provided with a screw device for thrusting it towards the centre, so that all the coils are wedged tightly together. As the armature is stationary there

FIG. 438.



ARMATURE OF MORDEY'S ALTERNATOR.

are no centrifugal forces to be considered, and the coils have to be supported only with a view of resisting the tangential drag of the field. This renders the insulation of the armature coils a very simple matter, and is of great importance in working at high volts. The revolving field-magnet forms an excellent fly-wheel, effectually neutralizing any pulsations due to irregularities in the stroke of the engine, and as there are no parts liable to fly out, a high speed of driving presents none of the difficulties that arise with many other types of machine. In Fig. 436, which gives a view of the complete machine, the field-magnets are almost hidden by the external webs which cover the spaces between the projecting poles to prevent too great a disturbance of the air by the rotating pole-pieces. The shaft, as shown in Fig. 437, is provided at one end with a thrust-bearing resembling that of a marine propeller, and the bearing blocks are made adjustable longitudinally, so that the field-magnet may be placed exactly symmetrically with respect to the armature. In the latest machines end-play is prevented by shoulders on the journals, this form being less liable to heat. The exciter is a small four-pole Victoria machine (p. 498), weighing but $\frac{1}{40}$ of the weight of the alternator: the excitation taking 1 HP. The electromotive-force in a 20 kilowatt machine is 1 volt per 8½ inches of conductor in this machine. The very low resistance of the armature, and almost complete absence of armature reactions, makes the machine almost self-regulating. One advantage in this type of machine is the little labour required in winding its coils; and the simplicity of the tooling and fitting of the iron portions is a great gain.

The following is a description of the 75 kilowatt (or 100 HP.) alternator depicted in Plate XXI. Output (as usually wound) 37·5 amperes at 2000 volts, when running at 500 revolutions per minute. As there are 12 poles, the number of periods is 6000 per minute or 100 per second. The armature consists of 24 coils, usually wound so as to be all united in series: each coil working at 83·3 volts and having a resistance of 0·051 ohm. The total resistance of the armature is 1·22 ohm; hence at full load the lost volts are $37{\cdot}5 \times 1{\cdot}22 = 55{\cdot}75$, and the watts lost by internal heating 1715. The armature coils are wound with copper strip 0·375 inch wide and 0·030 inch thick, the turns being separated by an insulating tape so thin as to be transparent. The polar gap is 0·75 inch across. The amperage at full load is no less than 3300 amperes per square inch. This figure, which in many types of machine would involve unsafe heating, is not high enough to do more than produce a gentle rise of temperature owing to the excellent conditions of ventilation. So it comes about that in this machine the limit of current-density is not fixed by risk of overheating, but by considerations as to the efficiency and the slope of the characteristic. For the other losses in the armature have been reduced to a negligibly small amount by attention to details. Loss by hysteresis there is none, owing to absence of any armature core. The eddy currents in the tape are trifling, it being so thin and needing no further lamination. Further, the coil-holders do not penetrate into the polar gap, but merely pass across the fringe of the field. They are moreover of German-silver, the high specific resistance of which alloy reduces the losses by eddy currents to $\frac{1}{16}$th or $\frac{1}{20}$th of what they would be if brass were used. That the waste is almost entirely confined to the i^2r loss is afforded by the fact that the machine when driven on open circuit, but excited to give its full voltage, only absorbs 3 HP., the armature keeping quite cool. This is a very important point in all machines intended for central station use, as the wasted power forms a very much higher percentage of the total power when machines are running with light loads, than when they are fully loaded. And it by no means follows that a machine which shows a high efficiency at full load will show a high efficiency at low loads during the day-light hours. This is a point which Mr. Mordey early recognized and strove to meet in his designs. The field-magnet coils are usually wound to take a current of 17·6 amperes at 65 volts; or requiring 1150 watts, at full excitation. The electrical efficiency may be calculated as follows. Nett output 75,000 watts; armature loss 1715 watts; field-magnet loss 1150 watts; total power absorbed 77,865 watts; electrical efficiency 96·32 per cent. The makers guarantee a commercial efficiency of 93 per cent. The closeness of agreement of the commercial efficiency with the electrical efficiency is a measure of the goodness of design; being a proof of absence of friction, hysteresis and parasitic currents. It is a curious point that in many machines these losses, though great at low loads, are not only proportionally but actually less at full load. But machines which show great losses at low loads are uneconomical for central station work.

The Brush Electric Engineering Company has just completed some large alternators of 250 kilowatt capacity, having a nett efficiency of over 95 per cent. These are provided with a special oil-pump, consisting of two toothed wheels about 1½ inches in diameter, geared to one another, and enclosed, which draw in the oil between the teeth and deliver it under the journals at a pressure of about 60 lbs. per sq. inch. There is a sight-drain for the oil, enabling the attendant to be sure that the lubrication is efficient. The following are particulars of a 250 kilowatt alternator:—

Field-magnet has 20 pairs of poles; revolving at 300 revolutions per minute gives 100 periods per second. Weight of revolving magnet and shaft 15 tons: total weight of machine 20 tons. Magnetization of poles, 7400 lines per square centimetres. Breadth of single armature coil, $7\frac{1}{16}$ inch ($= 9^{\circ}$); effective length of ditto 10⅜ inch; width of coil, ⅝ inch. Excitation on open circuit takes 2800 watts: at full load, 3650 watts, or less than 1½ per cent. of output. Drop in volts at full load, if excitation is constant, 4½ per cent; electrical efficiency (including excitation), 97 per cent.; guaranteed commercial efficiency, 93 per cent. The sliding connexions for the exciting current are made by two flexible strips of metal gauze, weighted at one end, which hang over the two contact-rings.

Some still larger machines of 500 kilowatts are being constructed from Mr. Mordey's designs.

Mr. Mordey has designed[1] a considerable number of alternative forms, all characterised by the combination of the two principles of simplicity of magnetic circuit and non-reversal of polarity in the armature. Some designs for machines of kindred type have been patented by W. Main.[2]

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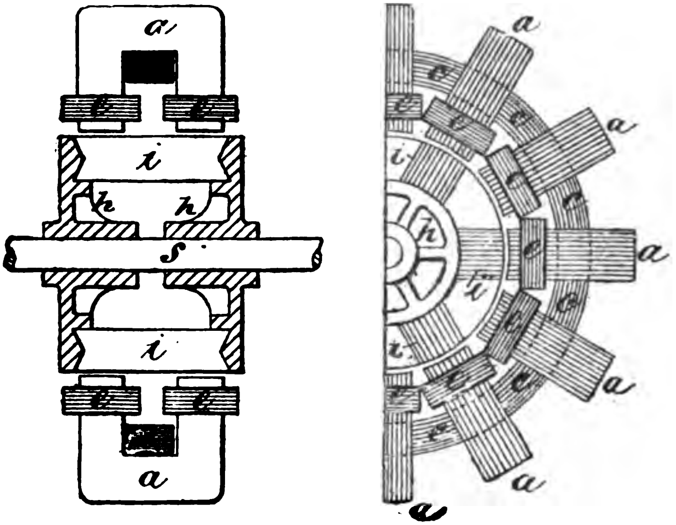
[1] Specification of Patent, 8262 of 1887.

[2] Specifications Nos. 15,858 and 16,032 of 1887. The device of employing field-magnets with a greater number of pole-pieces than of exciting coils had been previously employed by Holmes (Specification 2060 of 1868), and more recently by J. and E. Hopkinson.

INDUCTOR ALTERNATORS.

Mordey's Inductor Alternators.—An inductor alternator of Mordey's design is shown in Fig. 439. The armature coils *e* are placed upon

FIG. 439.



MORDEY'S INDUCTOR ALTERNATOR (First Type).

the ends of U-shaped iron stampings *a*, arranged in sets around a single exciting coil *c*. A number of plates of laminated iron *i*, fixed upon a central wheel, are carried past the outer masses of iron, and reinforce their magnetic circuits in alternating succession.[1]

Although in this form only a single annular field winding is used, the armature winding consists of a considerable number of coils. In a later patent[2] the same designer has suggested several forms in which he employs only a single annular winding for the armature as well as for the field. Fig. 439*a* shews the application of this principle in an inductor alternator, in which *c* is the exciting coil and *e* is the armature winding. This machine may be looked upon as an apparatus for periodically varying the mutual induction between two circuits, in one of which there is a steady current.

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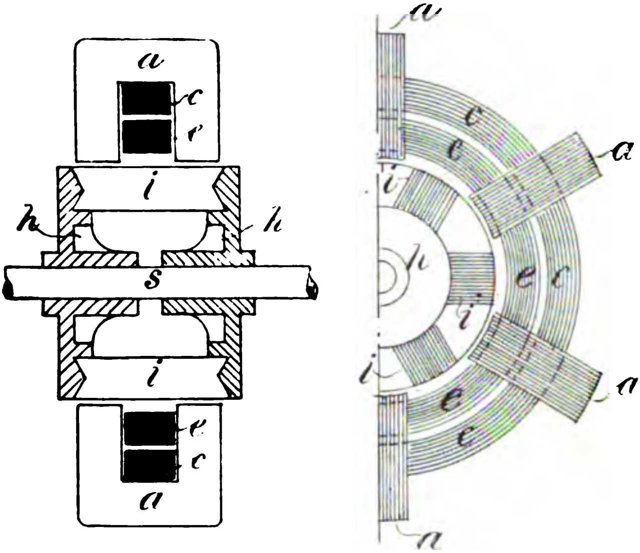
[1] This principle, suggested by several early workers (see Historical Notes, p. 11), was revived by the author of this treatise in 1883, in a form which is described in his Specification of Patent, No. 1639 of 1883, and which led up to Mr. Kingdon's. Drawings of this latter machine are given in *Electrical Review* xxii. 178, 1888.

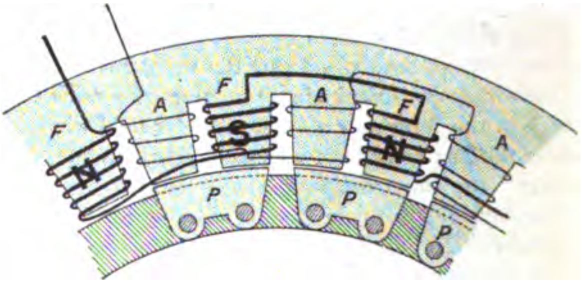
[2] No. 5162 of 1888.

FIG. 439A.



MORDEY'S INDUCTOR ALTERNATOR (Second Type).

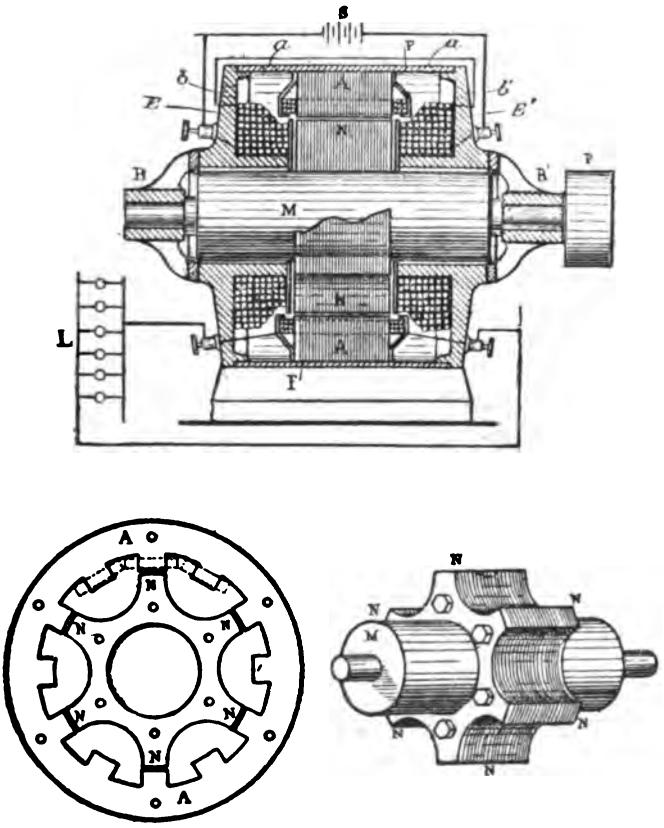
FIG. 440.



KINGDON'S INDUCTOR ALTERNATOR.

Kingdon's Inductor Alternator. — The last-mentioned machine closely resembles an earlier and successful design of Mr. J. A. Kingdon. In this dynamo the principle of fixing both armature and field-magnets is applied in a different fashion. A ring having a large number of internally projecting poles is entirely built up of laminæ of soft iron. The alternate poles A are wound with coils to serve as armature parts, whilst those between them F are wound with other coils

FIG. 441.



ELIHU THOMSON'S INDUCTOR DYNAMO.

to act as the magnet part. Upon an internal wheel are borne masses of laminated iron P, which in rotating produce rapid periodic reversals in the magnetic polarity of the cores of the armature parts, and set up alternate currents in the coils that surround them.

In the 50-kilowatt machine there are 16 field-magnet or primary coils, and 16 armature or secondary coils. The inductor wheel carries 16 inductor blocks each, just long enough to span the width of two successive coils on the poles of the outer ring. Its diameter is 4 feet 5 inches, and breadth 12 inches; speed 350 revolutions per minute. Two of these alternators supply the central station at Woking. Another was shown at Frankfort by Messrs. Woodhouse and Rawson.

ELIHU THOMSON'S INDUCTOR ALTERNATOR.—In this machine also, the only rotating parts are of iron. On a central cylinder of iron, M (Fig. 441), are fixed a number of plates stamped out to the form shown at N. Outside this revolving part is an armature A built of toothed core disks, having coils on the inwardly projecting teeth, which are twice as numerous as the projections of the inductor part N. Some fixed coils placed on either side of N are separately excited so as to make N a north pole, and the end frames of the machine south poles. Hence the inductor becomes virtually a rotating field-magnet, having a set of poles of but one polarity, which completes their magnetic circuit through the armature coils in alternate succession. Some large central station alternators on this plan, having a capacity of 375 kilowatts, have lately been constructed. The inductors are carried on a wheel 6½ feet in diameter. There are thirty-six armature coils.

Kennedy's Alternators.—Numerous ingenious designs of kindred type have been produced by Mr. Rankine Kennedy.

CONSTANT-CURRENT ALTERNATORS.

A variety of alternators for supplying currents of an unvarying number of virtual amperes for the purpose of arc-lighting in series has been evolved in the United States; the principal forms being those of Stanley[1] and of Heisler.[2] The principle of these machines is to so construct the armature that it has great self-induction. This is accomplished in the Stanley constant-current alternator by using in the armature a fine wire of many turns wound deep in nicks in the core-disks.

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[1] *Electrical World*, xv. 45, and xvi. 339, 1890; also *The Electrician*, xxiv. 623, xxv. 145, and xxvi. 20, 1890.

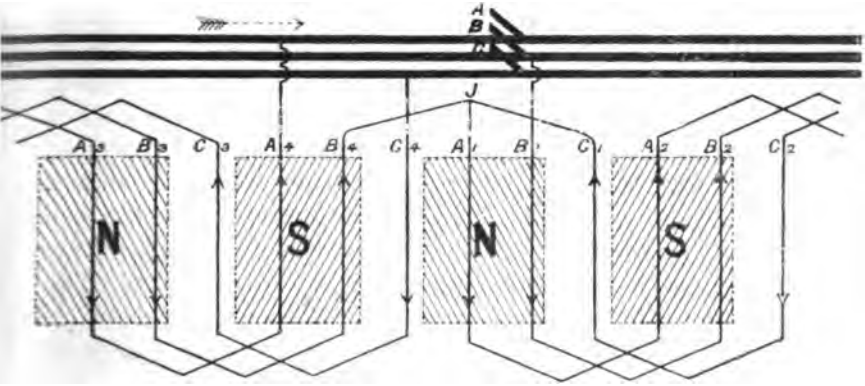
[2] *Electrical Review*, xxv. 207, 1889.

MULTIPHASE ALTERNATORS.

It has been pointed out on p. 642 that the separate circuits of the winding of Gramme's alternator would yield alternate currents which differ in phase from one another, and, therefore, must be used in different circuits. Quite recently alternators generating currents of different phases have come into vogue, not for lighting but for supplying power to motors of a special class (see p. 703), namely those requiring multiphase currents.

The principle of multiphase working consists in providing the armature of the alternator with coils grouped in sets of two, three, or more, which come successively into action in each period. Several ways of arranging such windings are further considered in Chapter XXIV. on Alternating Motors. For the present it will suffice to say that whether the armature be of ring, drum, pole, or disk type, it is always possible to arrange for multiple circuits by properly spacing the coils with respect to the field-poles, and the method is equally applicable to lap-windings and wave-windings. One example only is given here, of a three-phase winding. In Fig. 442 are shown three separate wave-windings A, B, and C, which are

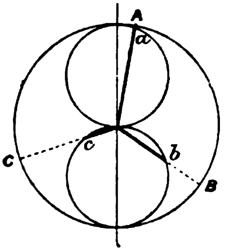
FIG. 442.



DEVELOPED DIAGRAM OF THREE-PHASE WINDING.

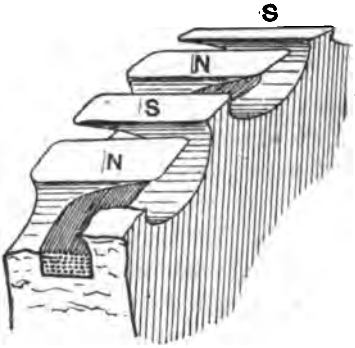
spaced out at equal distances from one another, the width between the separate active conductors being one-third of the pitch. At one point J these three windings form a common junction, whilst their other ends are supposed to be connected to three contact rings, to each of which there is a collecting brush. This figure should be compared with the ordinary alternator windings, Figs. 202 and 203, on p. 313. The winding shown would yield three currents differing in phase by 120°. The three-phase principle may be illustrated by a diagram such as Fig. 443 on the same plan as Fig. 396, p. 621. The three lines at 120° apart are supposed to rotate; and the lengths cut off by the two inner circles indicate the values of the varying electromotive-forces in the three circuits.

FIG. 443.



Brown's Three-phase Alternator.—This alternator, which was designed for supplying the currents in the famous transmission of power from Lauffen to Frankfort, in the autumn of 1891, was constructed at the Oerlikon works. Its aspect is shown in Plate XXVIII. The machine generates three currents each of 1400 amperes at a pressure of 50 volts, taking 300 HP. when running at 150 revolutions per minute. The armature, which is external, is stationary, whilst the field-magnet, which has 32 alternate poles, rotates within. The latter is shown separately in the second figure. The armature winding consists of 96 copper rods, each being 29 mm. in diameter, arranged in three sets of 32 each, connected as in Fig. 442. These rods, insulated within asbestos tubes, are buried in holes punched in the core-disks (see p. 347), just within the inner periphery. The core-disks, which are stamped out in segments, are assembled in a strong cast-iron frame, which can be moved bodily along the bed-plate, exposing the field-magnet for cleaning. The field-magnet is of great solidity and simplicity, having but a single magnetic circuit. The exciting coil is wound on the periphery of a sort of pulley of cast iron, to which are bolted two steel rims, each of which has 16 projecting horns. These horns project inwardly, the N-poles between the S-poles over the exciting coil in the manner sketched in Fig. 444. This arrangement, which in general resembles Mordey's, reduces the cost of construction and of excitation to a minimum. In fact, on open circuit only 100 watts are spent on excitation—one twentieth of one per cent. of the output; and at full load, when the armature reaction is a maximum, it is still far less than one per cent. This excitation is furnished by a small Oerlikon dynamo. For convenience of use with a turbine, the field-magnet is over-hung. The exciting current is conveyed to the rotating part by means of flexible metallic cords running over insulated pulleys, in lieu of the usual contact-rings and brushes. At full speed and normal voltage, the loss by friction and hysteresis is 3600 watts, or under 1·7 per cent. of the maximum output. The loss by resistance of armature windings at full load is 3500 watts, making total loss under 4 per cent., and commercial efficiency 96 per cent. The heating is, in the total absence of eddy-currents, quite negligible. The weight is 4½ tons. Alternators of this type will run as motors, synchronously, but with the great advantage over ordinary two-phase alternators of being self-starting.

FIG. 444.



SKETCH OF DETAIL OF FIELD-MAGNET.

Coupling of Alternate-current Dynamos.—The chief principles governing the working of two or more alternate-current machines on the same circuit were experimentally discovered by Wilde, and described by him in a paper published in the *Philosophical Magazine* as far back as January 1869. In the midst of the labour devoted during succeeding years to the development of direct-current machines, Wilde's paper appears to have been quite forgotten, and it was not until

Dr. Hopkinson independently took up the question and treated it in his lecture on "Electric Lighting," before the Institution of Civil Engineers in 1883, that attention was recalled to the subject. Dr. Hopkinson's method of procedure differed essentially from Wilde's in that he first deduced the behaviour of certain alternate-current dynamos under given conditions from theoretical considerations, and afterwards, when opportunity occurred, practically tested and verified his theoretical conclusions. In the following remarks we shall chiefly follow the line of argument used by Dr. Hopkinson.

In order that two or more alternate-current machines may work usefully together, it is easily seen that the periodic time of the alternations of one machine must be exactly equal to or at least some very small multiple of the periodic time of the other. In practice only the first case has been carried out hitherto. Let us consider then the case of two exactly similar and equal machines A and B, running at the same speed so that the periodic time of the alternations of electromotive-force is the same in each machine. If the phase[1] of these two machines happens to be exactly the same, and they are joined in series, then evidently the two electromotive-forces will be added together and the two machines will behave as one. But such a condition of affairs will be unstable; and if anything happens, such as a slip of one of the driving-belts, to alter slightly the exact agreement of phase, the mutual electrical action will *tend* to increase the difference of phase instead of counteracting it. In Fig. 445 let the abscissæ measured along O X represent time, and the vertical distances electromotive-force; then the curves A A A and B B B will represent the march of the alternations of electromotive-force in the two machines, the curve B B B, which lies to the right of A A A, being the one corresponding to the machine which lags behind the other in phase. The curve E E E, which is obtained by adding the ordinates of the other two curves, gives the resultant electromotive-force in the circuit at any instant. As shown on p. 627, the current will have the same periodic time as this last electromotive-force, but will lag behind it in phase. It may therefore be represented by the dotted curve I I I, in which the ordinates represent current instead of electromotive-force. Now the rate at which either machine is putting energy into the circuit at any instant is given by the product of the ordinate of I I at that instant by the ordinate of the electromotive-force curve for that machine at the same instant. Thus at the instant N the machine A is doing work at the rate N K × N G, and the machine B at the rate N A × N G. The meaning of the product being sometimes negative is that the machine is at that moment *absorbing* energy from the circuit. The *total work* done by either machine during a complete alternation of current is obtained by summing up for the whole alternation the above products, each multiplied by the small interval of time dt during which it can be assumed to be constant. This is most readily summed analytically, but may be done graphi-

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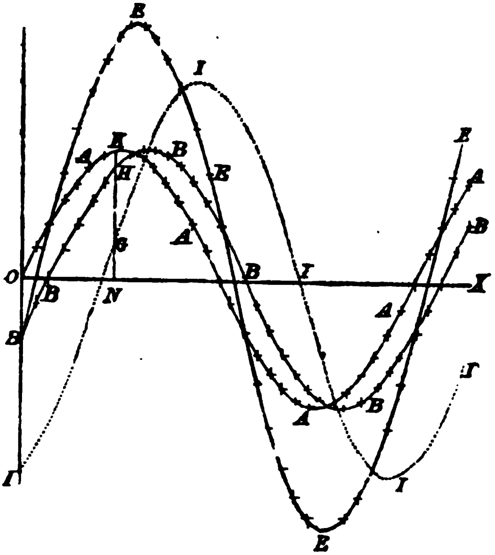
[1] By the phase being the same we mean that the maximum of positive electromotive-force occurs at *exactly the same instant* in each machine. In any other case the phases differ.

Fig. 445.



cally as follows. Plot a new set of curves, in which the abscissæ are the same as before, but the ordinates are the products of electromotive-force and current for each machine for each instant of time. The result will somewhat resemble

FIG. 446.

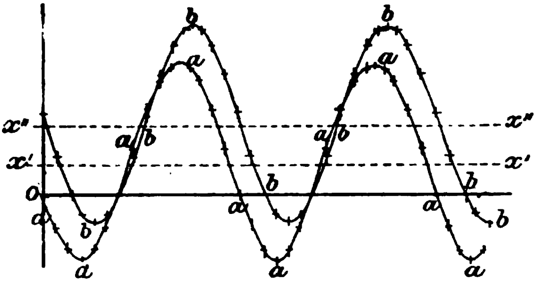


FIG. 447.

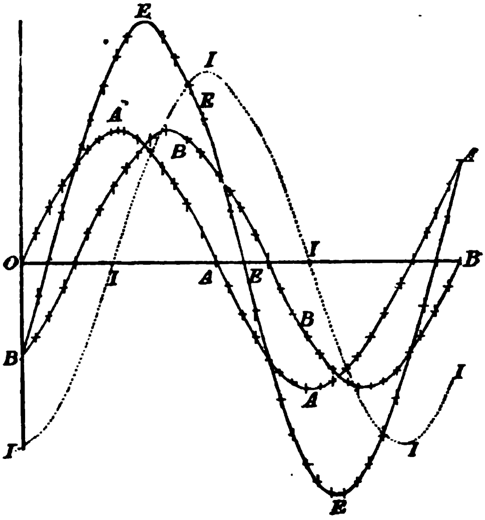
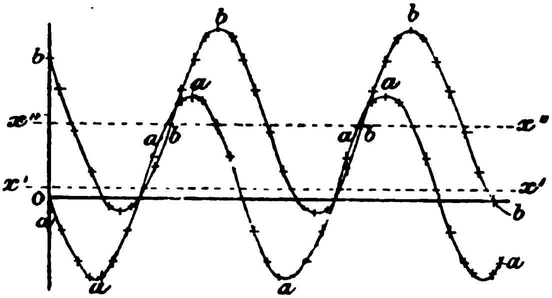


Fig. 446, which has been obtained thus from Fig 445. Here the curve *a a a* refers to machine A, and *b b b* to machine B. The total work is obtained by measuring the area included between each curve and the axis of abscissæ, remembering that areas *below* the axis are to be reckoned as *negative*, and arithmetically deducted. A moment's inspection of these curves will show that machine B is doing more work than machine A. In fact, the curve *a a a* is symmetrical about the horizontal axis $x' x'$, whereas the curve *b b b* is exactly similar to it, but is symmetrical about the higher axis $x'' x''$, and therefore the positive area included between it and the axis of time is necessarily greater than that for the curve *a a a*. The *lagging* machine B has therefore most work thrown upon it, and will consequently be retarded; thus the lag will be increased, and the resultant electromotive-force, and consequently the current, thereby diminished. But that the tendency will still be towards further lagging is shown in Figs. 447, 448, which are drawn in the same way and to the same scale as Figs. 445 and 446, but with increased lag of machine B. The lag will therefore continue to increase, and the resultant electromotive-force and current to diminish, until such time as the electromotive-forces of the two machines differ in phase by exactly half a period, and therefore directly oppose one another. In this case the resultant electromotive-force will be continually zero, and therefore no current will flow. Figs. 445 and 447 will be reduced to Fig. 449. This condition of affairs is stable, since if anything disturbs the exact opposition of phase the electrical action will tend to re-establish it.

FIG. 448.



Another deduction from the above proof is that the machines will theoretically work perfectly well in parallel. For let A *a* (Fig. 450) represent the collectors of machine A, and B *b* those of machine B; then, as shown above, if these are joined, A to B, and *a* to *b*, as in the dotted lines of the figure, no current will flow, and if an arc-lamp be placed in *b a* or B A it will not light up. In fact, A and B are both at their maximum positive potential simultaneously, and at the same instant *a* and *b* are at their maximum negative potential. But this is exactly the state of affairs which will enable us to obtain a current through the circuit P R *p* joined on to the wires A *a* and B *b* at the points P and *p*. With this arrangement the machines are working in parallel through the circuit P R *p*.

FIG. 449.

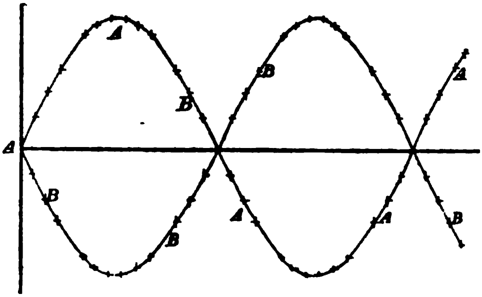
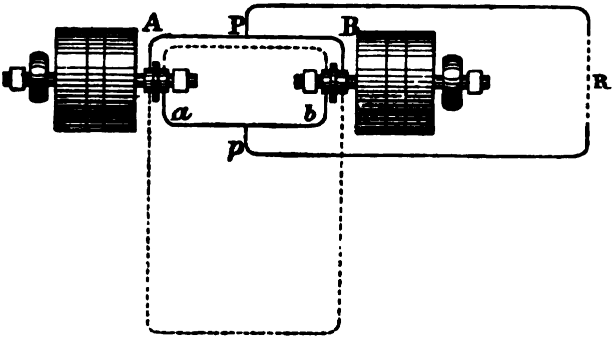


FIG. 450.



A still further deduction is that an alternate-current machine can be used as a motor. In this case machine B (the *lagging* machine) is the generator, and is doing positive work upon the current, whereas machine A is doing negative work upon the current, *i.e.* is receiving energy therefrom, and is therefore acting as a motor. The conditions are that the lag of one electromotive-force behind the other shall be greater than a quarter period, the lag of the current being as usual either equal to or less than a quarter period behind the *resultant* electromotive-force. These statements are readily proved by re-drawing Figs. 445 and 446 under the above conditions. Here is the result in Figs. 451 and 452.

FIG. 451.

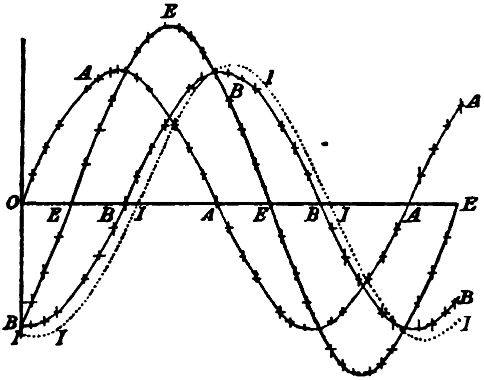
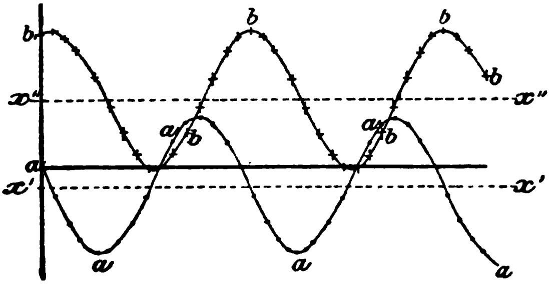


FIG. 452.



A more curious result still is that A can be driven as a motor by B *even if its electromotive-force is greater than that of* B. The proof is precisely the same as that just given, and is left for the student to work out for himself as an exercise.

All the curves given are for the same pair of machines, running at the same speed throughout, and with the same total resistance and inductance in the outer circuit. The lag of the current behind the resultant electromotive-force is therefore the same in each case (see p. 627).

It is scarcely necessary to say that the analytical proofs are in perfect accord with the graphic ones. A further result of the analytical method, which is not so amenable to graphic treatment, is that the energy wasted in eddy-currents in the iron when the machine is *short circuited* is *less* than when it is running on *open circuit*, and therefore the machine will be cooler when used to generate a current than when allowed to run without doing so. This fact has long been well known in connexion with alternating-current machines, and is well illustrated by the following experiments made by Dr. Hopkinson on a De Meritens machine:—

Power given to machine as measured on belt ..	3·1	4·8	5·6	6·5	5·4
Electric power developed	0·7	3·4	4·3	5·7	3·4
Power lost	2·4	1·4	1·3	0·8	2·0
Mean current in amperes	7·7	38·6	51·7	73·6	151

It will be noticed that the loss of power is *least* with maximum load.

The above conclusions have been brought by Dr. Hopkinson and Prof. Adams to the test of experiment with the three large De Meritens machines used for the investigation on "Lighthouse Illuminants" at the South Foreland.

Two of the machines were connected in parallel and clutched together until they had attained their usual speed, when they were unclutched and each was driven by its own belt. The electromotive-force on open circuit remained steady, the machines continuing to rotate in unison, and was the same as that of one of the machines when tested by itself. No current passed along the connecting wires. The circuit P R p (Fig. 450) was now closed through an arc-lamp; the machines continued to run as steadily as before, although a large current of 221 amperes was passing through the arc. Lastly, the lamp circuit was broken, the machines were short-circuited on one another, and the belt was thrown off one of them ; it continued to run at the same steady speed, being driven as a motor by the current from the other machine. Other experiments were made, all confirming the theoretical conclusions.

Dr. Hopkinson has pointed out that, assuming the adequacy of his equations, which suppose all magnetizing or demagnetizing actions in the armature to be absent, it results from his equations that two alternators running in parallel will tend best to keep in phase by mutual control when the ratio of their internal resistance to their coefficient self-induction is equal to 2π times the frequency. This proposition has been supposed by some to imply that the presence of self-induction in the armature is good for alternate-current machines, in order to assist them to run in parallel. It was therefore supposed that those machines having iron cores in their armatures were preferable to those having no iron. Indeed, Mr. Kapp[1] suggested at one time that to fit alternators for parallel running, either their armature resistance or their self-induction would have to be increased, thus reducing the efficiency of the plant. Against these views Mr. Mordey[2] has very clearly laid down the proposition that for successful parallel running both resistance and self-induction should be as small as possible, and all armature reactions should be as far as possible obviated by employing massive powerful field-magnets. He constructed two alternators which conformed to this leading principle, each capable of yielding 17 to 20 amperes at 2000 volts when running at 650 revolutions per minute, and making a frequency of 100 alternations per second. With these two machines he conducted a number of convincing experiments, which are described in the important paper which he communicated in 1889 to the *Institution of Electrical Engineers.* These two machines (each separately excited) ran perfectly when switched in parallel with one another: (1) when both were first brought to equal voltage and into agreement of phase, with or without a load of lamps on the circuit; (2) when excited to 1000 and 2000 volts respectively and separately brought into agreement of phase; (3) when excited to 1000 and 2000 volts respectively and switched together when out of phase, a sufficient current passing for an instant from one to the other to produce concordance of phase; (4) when separately excited to 2000 volts each, and switched together out of phase; (5) when after running together in parallel one was suddenly disconnected from its driving engine; (6) when after running together in parallel, steam was suddenly shut off from one engine; this alternator then running perfectly as a motor and driving the engine and shafting. In all these cases there was perfect synchronism. The change of phase needful to convert a leading into a lagging[1] machine need be only through a small angle; but as in the alternators of Mordey's pattern (p. 676) the momentum of the moving parts is very great, nothing but a very considerable rush of current for an extremely short time would suffice to bring about the needful change of phase. Accordingly, Mr. Mordey holds that self-induction and resistance and anything else that could retard, check, or choke the free rush of current would be detrimental to the prompt and efficient mutual controlling action of the two machines. That a strong mechanical action does take place when an alternator is suddenly converted from generator into motor, and is compelled to change its phase, is evidenced by a curious grunting sound which it emits at the moment. Sir William Thomson has expressed the opinion[2] that the armature current may, under the various phase-relations, produce considerable quasi-permanent magnetizing and demagnetizing actions which affect the mutual control. Experience, however, shows that if two machines are run with very weakly excited field-magnets their synchronizing power is practically nil, whereas when strongly excited their synchronizing power is enormous. This single fact shows that the ability to maintain synchronism depends on the forces which are due to the drag of the magnetic field on the armature conductor carrying currents. It therefore proves that *the essential fact in the maintenance of synchronism is the interchange of currents between the two machines, which interchange of current always sets up forces tending to so alter the phase-relations as to reduce such currents to a minimum.* This proposition, which is a mere extension of the universal law of action for electric motors (see p. 589), is applicable not only to those cases where one of the two machines is acting as a motor, but to the cases where the machines are both acting as generators. When two machines are being used as generators, in parallel, it is always possible to control the division of the load between them by controlling the amounts of exciting current supplied to their respective field-magnets. They adjust their own phase-relations to suit. It is therefore clear that the question whether the ratio of self-induction to resistance has any particular value, is of quite trifling importance in the question of synchronization. For this ratio is practically the same, no matter whether the field is strong or weak, and yet the synchronization is entirely dependent on the field being strong.

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[1] *Proc. Inst. Civil Engineers*, xcvii. 14, 1889.

[2] *Journal Inst. Electrical Engineers*, xviii. 591, 1889.

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[1] These terms refer, as above, to the leading or lagging of the electromotive-force with respect to the current.

[2] *Journal Inst. Electrical Engineers*, xviii. p. 667, 1889, in the discussion of Mr. Mordey's paper.

For further information on this subject the reader is referred to an article by Dr. G. Schmidt, in *Centralblatt für Elektrotechnik*, ix. 440, 1887, dealing with methods of indicating difference of phase in alternate-current dynamos, by Elihu Thomson, in *Electrical World*, vol. ix. p. 258, May 1887, and vol. xi. p. 39, Jan. 1888.

CHAPTER XXIV.

ALTERNATE-CURRENT MOTORS.

As pointed out on p. 694, an ordinary alternate-current generator may also serve as a motor having the following peculiarities: (1) it will not start itself, but must be first run up to its proper speed, and then switched into circuit; (2) when once so started it will run in absolute synchronism with the generator at all loads within its range of work. Many attempts have been made to devise self-starting alternate motors, there being now four well-established classes of such machines. The classification adopted is based upon that of M. Hospitalier.[1]

Class I.—*Synchronous Motors.*

This class includes all ordinary alternators having field-magnets either of permanently magnetized steel, or separately excited from some independent source, or excited from their own currents by the intervention of a special commutator, as in the self-exciting alternators of Wilde (p. 646), of Zipernowsky (p. 662), and of Elihu Thomson (p. 660). The essential feature of these machines consists in the fact that the field-magnet remains of unvarying polarity. Ordinary two-phase alternators are not self-starting as motors: but multi-phase alternators, when fed with currents in appropriate phases, are self-starting provided the initial load is not too great, since the successions of phase in the armature windings produce a rotating magnetic field which causes the motor to rotate at first slowly, then more rapidly, up to complete synchronism.

The properties of ordinary alternators as synchronous motors have been studied by Wilde,[1] Hopkinson,[2] Adams,[3] and Mordey.[4]

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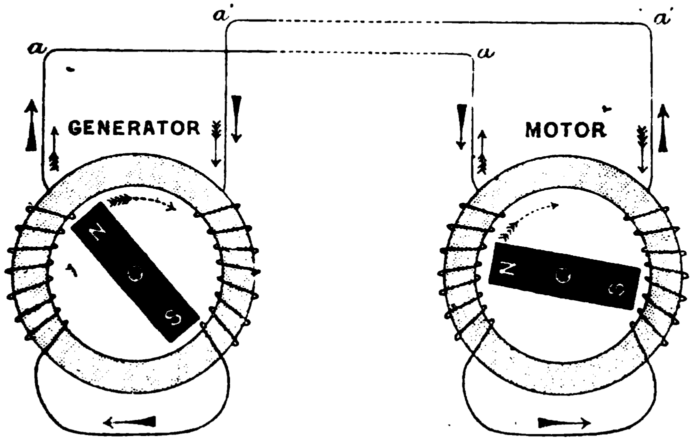
[1] *Société Française de Physique*, July 17, 1891.

Consider the case typified in Fig. 453, in which two similar machines are used as generator and motor. In these the field-magnet rotates within a laminated ring-wound armature. The motor is supposed to have been started and to have settled into almost complete opposition of phase to the generator; the current being represented as in phase with the electromotive-force of the generator and opposed to that of the motor. Two lines are needed, one for the out-going, the other for the return current. Should the motor lag in consequence of an increase of load, more current will flow, making the torque greater.

FIG. 453.



TRANSMISSION BY TWO-PHASE ALTERNATORS.

CLASS II.—*Laminated Field Motors.*

As pointed out on p. 590, the direction of rotation of any ordinary series-wound motor is the same irrespective of the direction of the current supplied to it. Hence such a motor ought also to run when fed with alternating currents.[1] But in this case it is essential that the field-magnets be carefully laminated; otherwise they will be over-heated with currents induced in the solid iron. Such laminated motors have been successfully used on a small scale. Shunt-wound laminated field-motors should similarly run with alternate currents: but the great self-induction of the magnet-circuit tends to introduce a phase-complication. Mr. Ll. B. Atkinson has suggested[2] several combinations of such motors to secure uniformity of running. In all two-phase motors there is of necessity a discontinuity in the driving forces, seeing that twice in each alternation the current dies down to zero. The effect of this on the motor is the same as though there were simultaneously acting a constant torque and a rapidly oscillating torque tending to rack the coils backward and forward. Further, the rapid reversal of the magnetism of the iron in the field tends to waste power by hysteresis. To minimize this source of loss, Mordey[3] has proposed to pass the exciting current through a commutator on the shaft of the machine, so that as the motor acquires speed the frequency of the alternations in the motor itself is reduced, until synchronism is attained, the current then being an intermittent direct current, and the torque being a maximum. Another mode of avoiding this loss is to omit all iron from the machine. Such a motor is of relatively small power; but it is used with great success in Elihu Thomson's electric meter.

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[1] *Proc. Lit. Phil. Soc. Manchester*, Dec. 1868; also *Phil. Mag.*, Jan. 1869.

[2] *Journal Soc. Teleg. Engineers*, xiii. 496, 1884.

[3] *Ibid.*, p. 515, 1884.

[4] *Ibid.*, xviii. 592, 1889.

Another sub-class of motors under this heading is based upon the forces set up by the reaction of eddy-currents on the field which generates them. The classical experiments of Elihu Thomson[4] on the repulsions observed in closed circuits when placed in an alternating magnetic field, led him to suggest a form of motor in which the circuits of field-magnet and armature are entirely disconnected from one another.

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[1] See remarks of Alex. Siemens, *Journ. Soc. Teleg. Engineers*, xiii. 527, 1884.

[2] Specifications of Patents, 16,852 of 1888, and 7895 of 1889.

[3] *The Electrician*, xxiii. 346: also Specification of Patent, No. 15,555 of 1887.

[4] *Electrical World*, ix. 258, May 1887; also *The Electrician*, xxv. p. 35 *et seq.*, May 16, 1890, in a series of articles by Prof. Fleming. See also an abstract account in the author's work on *The Electromagnet*, p. 338.

This machine may be regarded as a species of transformer in which the rotation is produced by a series of mechanical reactions between the currents in the primary coil (acting as field-magnet) and the secondary coil acting as armature. A closed coil in such a field always tends to move so that the magnetic flux through it is a minimum. If an ordinary ring or drum motor be taken (with laminated field), its field-magnet disconnected from the armature and excited by the alternate-current, and the brushes then simply connected together (so as to close the armature-circuit on itself) and advanced through about 45°, the motor will run and be self-starting.

CLASS III.—*Multi-phase Rotatory Field Motors.*

In 1885 was propounded, by M. Marcel Deprez, the geometrical notion that a rotating magnetic field might be produced by the combination at right angles of two alternating currents (varying in sine-functions of the time) which differed by a quarter period from one another in phase. In 1888 the idea of producing a rotatory field by the use of two currents differing in phase, independently led Professor G. Ferraris,[1] of Turin, Mr. Nikola Tesla,[2] of New York, and M. Borel,[3] to the production of rotatory-field motors. Tesla in particular worked out a large variety of forms on this plan, and gave them practical shape. The practical importance which rotatory-field motors have since attained renders needful a careful exposition of this principle of action.

Theory of Rotatory Field.—Referring to Fig. 395, p. 620, in which a point is supposed to move at a uniform speed round a circle, let the angle P O M through which the radius O P has turned from the zero point be called θ, then P M = sin θ, and Q P or O M = cos θ, if the radius be taken as unity. The circular motion, if projected on a vertical line will give a simple-harmonic vertical motion, or if projected on a horizontal line will give a simple-harmonic horizontal motion.

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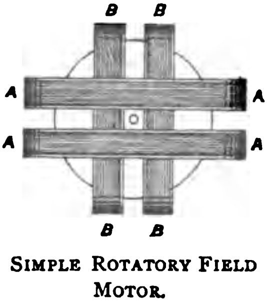
[1] Rotazioni elettrodynamiche, *Turin Acad.*, xxiii. March 1888.

[2] *Electrical World*, x. 281, June 1888; xv. 250, 1890; xvi. 101, 1890.

[3] *La Lumière Électrique*, xxix. 51, 1888.

Every engineer knows how readily a rotatory motion can be converted into two rectilinear motions at right angles to each other by causing a crank-pin to operate two connecting-rods. And in this case the two rectilinear motions will differ in phase by a quarter period, for one will be at the middle of its stroke when the other is at the end. Conversely, it is possible to produce a circular motion by compounding together at right-angles two rectilinear (simple-harmonic) motions that differ exactly one quarter period in phase, so as to produce a circular one. If the difference of phase is not exactly a quarter period, the resulting motion will be elliptical instead of circular. When two alternating currents differing exactly a quarter period in phase are carried around two magnetizing coils placed at right angles to one another, thus tending to produce two separate magnetic fields alternating across one another, their conjoint action will result in a rotating magnetic field. Ferraris found that in such a field not only will pivoted magnets rotate, but masses of iron, both solid and laminated, also disks and cylinders of copper, the drag on these being due to the eddy-currents generated in them precisely as in the classical experiments of Arago, in which copper disks were set into rotation in the presence of a rotating magnet. Fig. 454 illustrates a simple form of Ferraris's motor having a copper cylinder pivoted within two sets of coils A A and B B which lie at right angles to one another. If the two independent magnetizing forces follow sine-functions, and are exactly at right angles and differ exactly a quarter period in phase, the torque will be uniform. But if the phase-difference is not an exact quarter period, or the coils not exactly at right angles, the torque will have two maxima and two minima in each period, corresponding to the elliptical motion in the mechanical analogue.

FIG. 454.



SIMPLE ROTATORY FIELD MOTOR.

ILLUSTRATIONS OF ROTATORY FIELD TRANSMISSION.

In Fig. 453, p. 701, the case of ordinary two-phase alternators was illustrated. In this case there is a mere oscillatory field, magnetism in each part of the armature simply alternating in polarity. Such an alternator has dead points, and cannot start itself.

Four-phase Currents.—Now suppose that beside the two coils A A′ on each machine there are wound other two B B′ between the former pair, and that these are connected through a new pair of lines *b b* and *b′ b′*, Fig. 455. It is clear that a second set of alternating currents will be set up in B B′ which will be exactly a quarter-period in phase behind those in A A′. In fact the two currents will be represented by the two waves of Fig. 456. The electromotive-force in A will be greatest just when the pole of the magnet is passing its middle, for at that instant the rate of change in the magnetization of its core is a maximum. And the maxima for the B coils will correspond to the zeros for the A coils and *vice versâ*. The currents in the A coils of the motor, tending to drag forward the pole of the field-magnet, will not have died down to zero

FIG. 455.

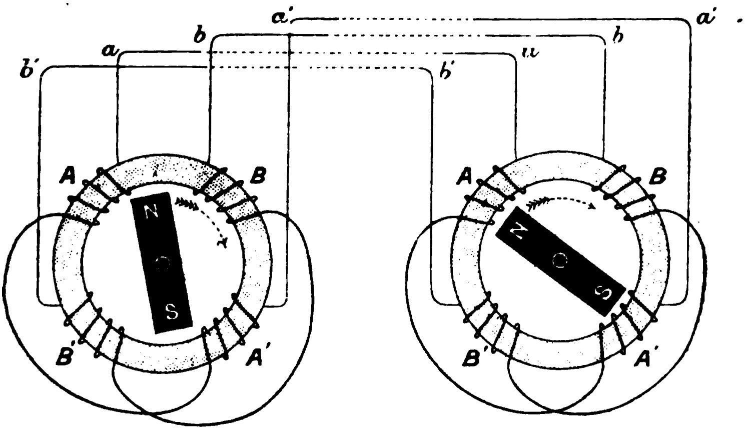
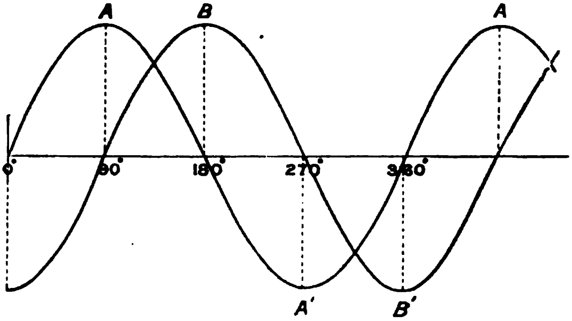


ILLUSTRATION OF FOUR-PHASE TRANSMISSION.

before the currents in the B coils will have already begun ; so that there is no dead point. It is easy to see that in the motor there will be a regular displacement around the ring of the resultant poles. At the moment when the current in A A′ is at a maximum that in B B′ will be zero, and the magnetizing action of A A′ will be to produce two double-poles in the ring at opposite ends of a diameter right under

FIG. 456.



TWO ALTERNATE CURRENTS DIFFERING BY A QUARTER PERIOD.

the middle of the B B′ coils. As the current in A A′ dies down that in B B′ begins and increases, and therefore shifts the pole forward. When the currents in A A′ and B B′ have become equal A and B will act together as one coil, while A′ and B will act together as another coil, the resulting poles lying now between B and A′ on the right and between B′ and A on the left. When the B current is at its maximum the poles will lie right under the middle of the A coils. A pair of travelling poles are therefore produced in the motor ring by the currents coming from the generator, and the magnet in the motor is continually trying to catch up these travelling poles. The motor will be self-starting if its magnet is not too powerful, and will run up in speed until synchronism is attained.

Since there is an actual production here of a travelling polarity in the ring of the motor, it follows that any mere mass of iron, a cylinder for example, placed in the rotating field will be set into rotation, though not necessarily synchronously. And a cylinder of copper would be dragged round by the eddy-currents induced in it. But if such eddy-currents were permitted to circulate at random in the mass of copper there would be much waste of power in heating, since the only useful currents for driving are those that flow at right-angles to the magnetic lines and at right-angles to the direction of motion, or, if oblique, their resolved parts in this direction. Hence it is better to make the moving part as an iron core surrounded by appropriate closed coils of wire within which the induced currents are confined. Such closed-circuit windings have been used by Tesla and others. Tesla's motors have been in successful use in the States, the standard size being a 7 HP. motor weighing 340 lbs., and having a nett efficiency over 85 per cent. A special form due to Dobrowolsky[1] consists of a cylinder of iron within the periphery of which are embedded—with or without insulation—a number of stout copper conductors lying parallel to the axis, their ends being united together so that they form closed circuits. A mere disk of copper at each end—forming with the conductors a sort of squirrel-cage of copper filled with iron—answers excellently. Or each conductor on the periphery may be joined by a connector (as in Fig. 457) to each of the other conductors which lies in the corresponding position of symmetry. Dobrowolsky preferred, in the motor used for the Frankfort transmission in 1891, to invert the arrangement, fixing the closed copper circuits and their core, and using as the rotating part that corresponding in Fig. 458 to the ring. It had three separate circuits not closed within the

FIG. 457.

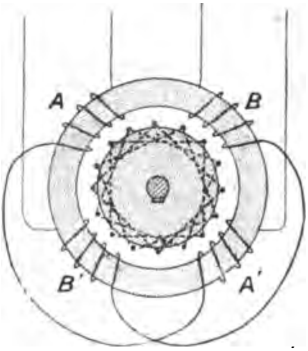


DIAGRAM OF A ROTATORY FIELD MOTOR.

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[1] *Elektrotechnische Zeitschrift*, xi. 341, 1890; also *Electrical World*, xv. 442, 1890.

machine but communicating with external resistances through contact rings. It was thus possible to prevent the enormous rush of induced current which otherwise might occur at starting, and which, though it would not harm the motor might have an injurious reaction on other parts of the system The external resistance could be cut out when the motor had got up its speed.

When such rotating combinations of copper and iron are used it becomes a question which part of the machine should be considered as armature, and which as field-magnet. If the ring is regarded as armature, then the copper and iron combination must be looked upon as a field-magnet which is self-magnetized by the eddy-currents in the copper, and which is continually trying to catch up the rotating poles outside it so as to reduce those eddy-currents to a minimum and keep its magnetic polarity constant. If, however, the ring be looked upon as the equivalent of a rotating magnet, then the combination of copper and iron must be considered as an armature in which currents are induced, and which is driven by the reaction of these currents.

So far it has been supposed that the two circuits of the A and B coils were kept separate, requiring four wires. As a matter of fact, only three wires are necessary; for a single common return might be provided for the *a* and *b* wires instead of two separate wires, the current in the return being the algebraic sum of the currents in *a'* and *b'* at every instant, and therefore having a maximum value 1·4 times as great.

Three-phase Currents.—Another mode of using three wires is to generate three equal currents differing in phase by ~~180°~~ or by 60° from one another. The three-phase alternator of Brown, used at Lauffen, was described on p. 688. Three-phase motors have been suggested by Tesla and others. An illustration of the three-phase system is afforded by Fig. 458, in which the rings are wound with three coils all joined at their ends and united to the three lines. In this case the current in any one line is equal to the algebraic sum of the currents in the other two, and, with the arrangement shown, the phase of the currents in any one of the lines is intermediate between the phase of the currents in the two coils feeding it. For example, the current in *a* is intermediate in phase between those in coils P and Q in the generator. Further, in the motor the current in P is intermediate in phase between the currents in *c* and *a*. As the magnet rotates in the generator a travelling pole will be produced in the ring of the motor as before. It will be noted that the coils here constitute a closed circuit. There are indeed several ways of connecting up three coils so as to produce the rotatory effect, the following being possible: (1) each of the three coils might be independently joined by two wires to the ends of the three corresponding coils, requiring six lines; (2) three ends of the three coils might be independently joined by three wires to the three corresponding ends of the coils in the motor, their three other ends being united to a common return line, so involving four wires; (3) the three coils *a*, *b*, and *c* may be simply joined at a common junction J (Fig. 459), from which they branch star-wise each to its own line; (4) the three coils may be joined as *p*, *q*, and *r* in Fig. 460, in a closed mesh

FIG. 458.

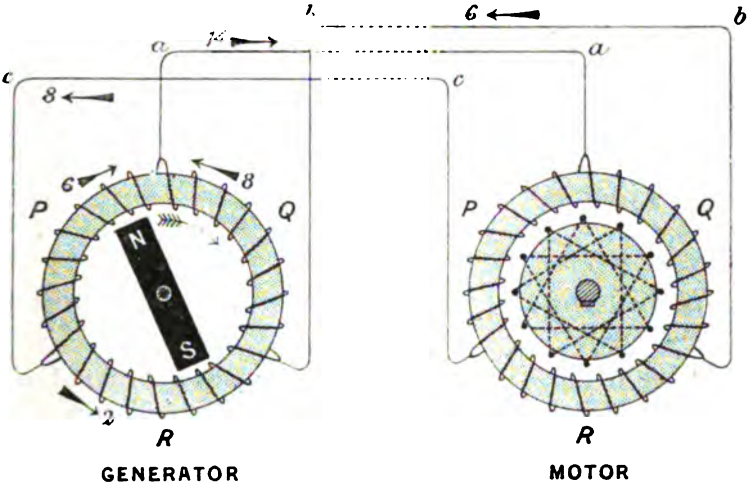
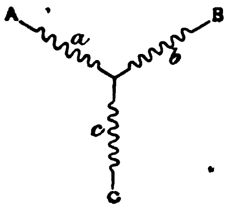


ILLUSTRATION OF THREE-PHASE TRANSMISSION.

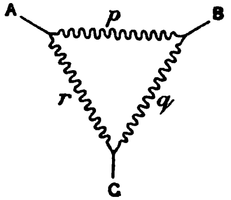
joined with the three lines at its corners. In this case the phases of the currents in *p*, *q*, and *r* are intermediate between those of the three currents in the lines; (5) six coils may be used as in Fig. 461, which shows the way of getting a six-phase effect out of a three-phase current by combining the star and mesh arrangements; (6) by merely winding a coil left-handedly instead of right-handedly the phase of its magnetizing force is reversed. For example, a reversed coil inserted in *a* (in Fig. 459) would give an effect differing 180° in phase from *a*, and therefore intermediate between *b* and *c*. By constructing a star with reversed coils in each branch, six phases can thus be got from a three-phase current.

FIG. 459.



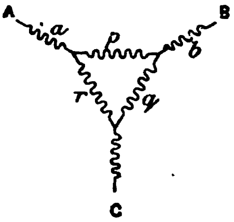
STAR COMBINATION.

FIG. 460.



MESH COMBINATION.

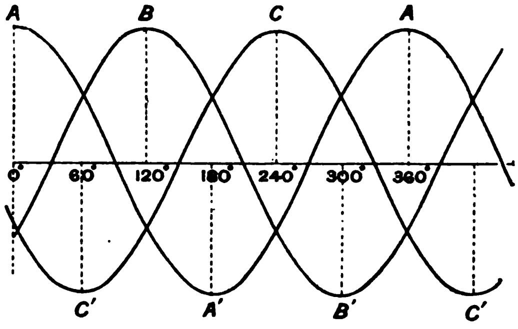
FIG. 461.



STAR AND MESH COMBINATION.

The mode in which the three currents overlap in phase is shown in Fig. 462, the phase difference being here 120°. Three currents with phase-difference 60° will also serve for rotatory work, and can be converted into three of 120° by merely inverting the connexions of one of the coils at each end. Dobrowolsky, who applied the name *Dreh-strom*, or *rotatory current*, to the system of currents alternating in periodic succession of phases and producing a rotatory field, has urged the superiority of the three-phase arrangement over four-phase, on the ground that if one constructs for such curves as Figs. 455 and 462, the resultant curve, the latter will show less variations in the case of the three-phase combination, the fluctuations of the ordinates being 40 per cent. in the resultant of the four-phase and only 15 per cent. in that of the three-phase. This assumes the waves to be of sine-form; which is not necessarily true. Moreover, adding sine and cosine ordinates is not the same thing as forming their true oblique resultant, which is their vector-sum, by the ordinary rule for compounding forces.

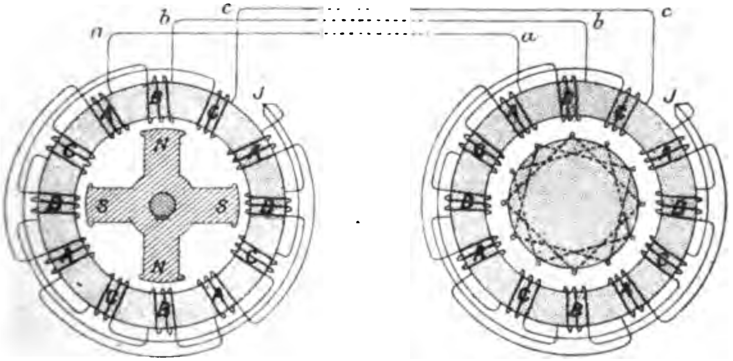
FIG. 462.



THREE-PHASE CURRENT CURVES.

A further illustration of the three-phase current is afforded by Fig. 463, in which the rings are multipolar, being wound

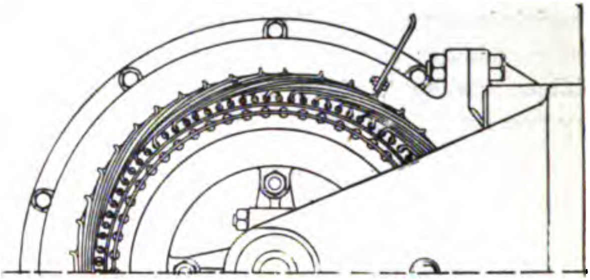
FIG. 463.



THREE-PHASE MULTIPOLAR TRANSMISSION.

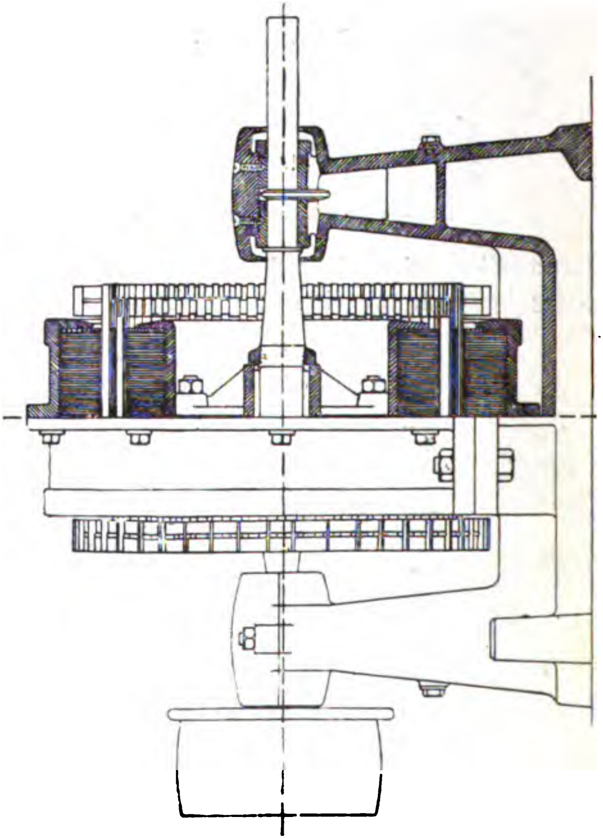
with twelve coils, producing four rotating poles. In this case there are both right-handed and left-handed coils, giving six phases of currents at 60° apart in period. The connexions constitute a star-combination, the three circuits having a common junction J at each end.

Fig. 465.



Half End-Elevation.

Fig. 464.

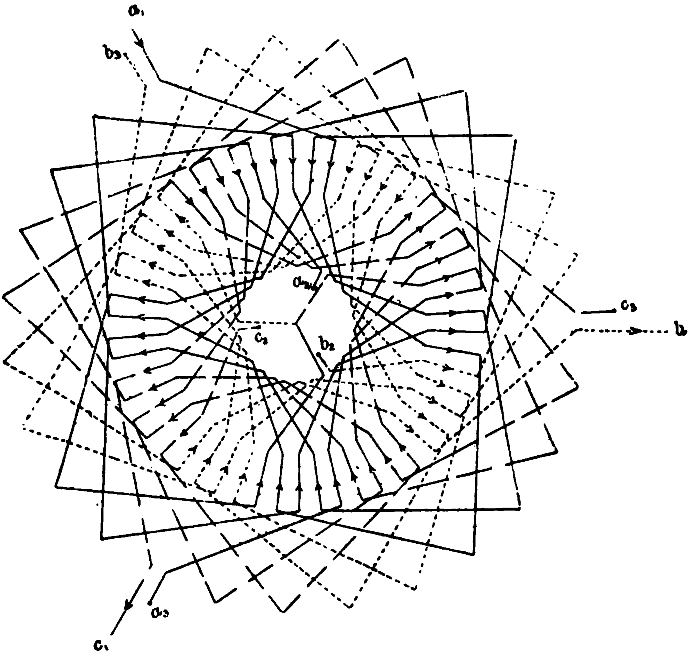


Brown's Three-phase Motor, Elevation.

Brown's Three-phase Motor.—No details have been published respecting the 60 horse-power three-phase motor used in the Frankfort transmission, which was constructed by the Allgemeine Elektrizitäts Gesellschaft of Berlin, from the designs of Dobrowolsky.[1] In the absence of such information, some drawings are here given of another somewhat similar motor designed by Mr. C. E. L. Brown.[2]

This motor gives out about 20 horse-power at 1200 revolutions per minute, when supplied with three-phase currents at 50 volts alternating with a frequency of 40.

FIG. 466.



BROWN'S THREE-PHASE MOTOR: SCHEME OF WINDINGS.

The general build of this motor recalls that of the three-phase alternator used at Lauffen, all the copper conductors being round bars which pass through perforations in the core disks.

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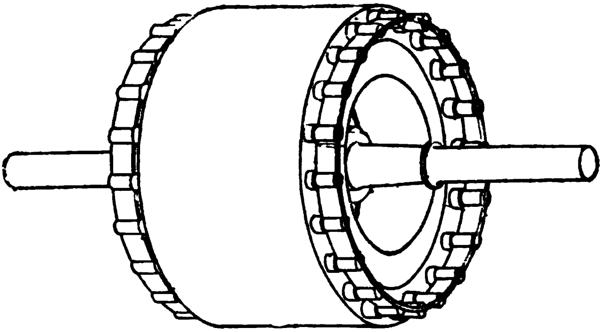
[1] See *Electrical Review*, xxix. 556, 1891.

[2] *Elektrotechnische Zeitschrift*, xii. 657, 1891. See also *The Electrician*, xxvii. 657, 1891.

In the outer stationary part are 90 conductors of about 40 sq. mm. section, each joined by end connectors of curved copper strip, which connect over spans of a little less than 90° in a wave-winding according to the scheme indicated in Fig. 466. This produces four travelling poles. The rotating part, which is also constructed with perforated core-disks, has 54 copper rods, each of 100 sq. mm. area. These are simply connected together at their ends by copper rings. There are 95 kilos. of copper in the rotating part, and 20 in the fixed windings. The weight of iron in the rotating part is 70 kilos., in the fixed part 100 kilos. There are no sliding contacts of any kind, and the whole motor runs quite cool. The difference in speed between no load and full load is about 3 per cent. The torque at starting was over 40 meter-kilogrammes. The total weight is about 420 kilos., and the commercial efficiency about 90 per cent.

FIG. 467.



ROTATING PART OF BROWN'S MOTOR.

Other Multi-phase Motors.—In another type of three-phase motor by Siemens and Halske, the three currents pass first through coils on an outer ring, producing a rotating field, and then are led by three brushes bearing on a commutator into a rotating armature. Schuckert & Co., Haselwander, Bradley, and Wenström have also constructed multi-phase motors.

CLASS IV.—*Rotatory Field Motors with Two-phase Currents.*

It is possible by various means to produce a rotatory field without resorting to three or four-phase currents. Many years ago De Fonvielle discovered that an iron disk pivoted within a coil supplied with an alternate current was maintained in rotation if once started in either direction.

Ferraris produced rotation in his motor by connecting one of the pairs of coils in the circuit of an ordinary alternate current, whilst the other pair were connected as a shunt to the circuit, with an inductive resistance included in order to retard the phase. Borel attained a similar result by using iron cores in one pair of coils. Schallenberger, in the mechanism of his meter, introduces a neat principle. The alternate current is led into two large coils which pass under and over the rotating iron wheel. Within these coils, and also surrounding the wheel, are two other coils, closed on themselves, made of brass stampings. In these coils secondary currents are induced, and these are different in phase by not quite 180°. But these secondary coils do not lie parallel with the primary coils, being set purposely at an angle of about 40° to them. Here, then, are two alternate currents, in different phases, acting at an angle. In the Borel-Ferranti meter another device is adopted. The pivoted wheel of iron or copper is placed between two field-magnets of laminated iron, each provided with a single elongated curved pole-piece.[1] The limbs of this field-magnet carry coils for the alternate current; whilst upon the prolongations or horns are placed closed windings of copper in which the alternating magnetic fluxes set up eddy-currents. The effect of these eddy-currents is to oppose the change of the magnetism in the core; with the result that they retard the propagation of the magnetic pole along the cores towards the tips of the horns, producing the phenomenon of an alternate succession of north and south poles travelling along the pole-pieces toward the tip, and there dying out.

A mode of splitting an alternate current into two alternate currents differing in phase from one another has been proposed by MM. Hutin and Leblanc,[1] for use in a rotatory field motor. When the current from the line arrives at the motor it is led into a divided path, into one branch of which a condenser of suitable capacity has been inserted, whilst into the other branch a coil possessing self-induction is intercalated. The former tends to accelerate[2] the phase of the current in its branch, whilst the latter retards the phase in the other branch, thus producing the desired phase-difference.

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[1] *Electrician*, xxv. 32, 1890.

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[1] *La Lumière Électrique*, xl., 1891.

[2] A condenser acts as a negative and reciprocal self-induction. Thus, whilst a self-induction L tends to produce a lag such that $\tan \phi = 2 \pi n L \div R$, a condenser of capacity K tends to produce a negative lag (*i. e.* a lead) such that $\tan \phi = -1 \div 2 \pi n K R$. See p. 635.

CHAPTER XXV.

TRANSFORMERS.

DURING recent years methods of distributing electric energy have come into vogue, in which, for the sake of economizing the cost of the metallic conductors, distribution is effected at a high electromotive-force or electric pressure from the central generators, and is received at different points by apparatus known as *transformers*, which transform the electric energy supplied to them, and give it out again at a lower electromotive-force or electric pressure.

To comprehend fully the bearing of the matter, it must be remembered that the energy supplied per second is the product of two factors, the current and the pressure at which that current is supplied; or, in our notation,

$$\mathcal{E} i = \text{electric energy per second (in watts).}$$

The magnitudes of the two factors may vary, but the value of the power supplied depends only on the product of the two; for example, the energy furnished per second by a current of 10 amperes supplied at a pressure of 2000 volts is exactly the same in amount as that furnished per second by a current of 400 amperes supplied at a pressure of 50 volts; in each case the product is 20,000 watts. Now the loss of energy that occurs in transmission through a well-insulated wire depends also on two factors, the current and the resistance of the wire, and in a given wire is proportional to the square of the current. In the above example the current of 400 amperes, if transmitted through the same wire as the 10-ampere current, would, because it is forty times as great, waste sixteen hundred times as much energy in heating the wire. Or, to put it the other way round, for the same loss of energy one may use, to carry the 10-ampere current at 2000 volts, a wire having only $\frac{1}{1600}$th of the sectional area of the wire used for the 400-ampere current at 50 volts. The cost of copper conductors for the distributing lines is therefore very greatly economized by employing high pressures for distribution of small currents.

For transforming from high pressures to low, several kinds of apparatus are known, namely :—

1. *Storage Batteries.*—A large number of these to be charged in series at a high potential: the series afterwards divided up or rearranged so as to discharge larger currents at lower pressure. This system is applicable to direct-current working only, not to alternate currents, and has the advantage of storing the consumer's supply.

2. *Induction Coils*, also called for this purpose *Secondary Generators*, or *Transformers*, or *Converters.*—This system will only answer with alternating currents, which being transmitted through the distributing mains at high pressure, and traversing the primary wires of the induction-coils, set up in the secondary wires currents which feed the separate circuits of lamps at the desired low pressure.

3. *Motor-Generators.*—These are either two separate machines: a motor, adapted to receive small currents at high potential, and be driven by them, and a dynamo, driven by the motor, and capable of generating large currents at low potential; or they consist of single machines having a double-wound armature, one set of windings of fine wire to receive the incoming currents at high potential, and another set, of thick wire, to furnish the outgoing currents at low potential.

4. *Commuting Transformers.*—These are a variety of the last, but neither armature nor field-magnet revolves, the polarity of the magnetic circuit being caused to vary by special commutators.

5. *Condensers.*—It is theoretically possible to employ condensers for transforming alternate currents, but their use is not yet practical.

Storage batteries we cannot here discuss; motor generators will be very briefly touched upon. Induction-coil transformers for alternate currents being a species of dynamo-electric machine, will be dealt with only as such: space does not admit of discussion of the various systems of distribution in which they are employed.

HISTORICAL NOTES ON TRANSFORMERS.

The first induction-coil was used by Faraday,[1] and consisted of a solid iron ring six inches in diameter and seven-eighths of an inch thick, having a primary wire seventy-two feet in length, and a secondary sixty feet in length, coiled around opposite parts (Fig. 471, No. 1). Small modifications were made by Masson,[2] who introduced a bundle of iron wires as core; Pohl,[3] Wright, Callan, Henley,[4] Dove,[5] who examined the properties of various kinds of iron cores and the damping effects of solid metal conductors and tubes; Sinsteden,[6] Magnus,[7] who also investigated the effects of the form of the iron core; Stöhrer,[8] who constructed the vertical pattern of coil; Ritchie,[9] who suggested the use of cloisons or partitions in winding the secondary, where high insulation was wanted; Ruhmkorff,[10] who gave the spark-coil its classical proportions; and Varley,[11] who in 1856 described a form of induction-coil having a laminated and closed magnetic circuit, closely resembling some of the modern forms of transformers. Various suggestions for use of induction-coils in distributing current for electric lighting were made by Jablochkoff,[12] who proposed to place in the circuit of an alternate-current machine, at different points of the circuit, the primary coils of a number of transformers, the secondary coils of which were used to supply lamps of the "electric-candle" type, and by Sir C. Bright,[13] who proposed similarly to distribute currents to vacuum-tube lamps. Jablochkoff, and later Edwards and Normandy,[14] suggested a peculiar construction of copper-strip conductors, set edge-on, in place of round wires in the coils. More practical forms of transformers were suggested by Fuller,[1] and by De Meritens.[2] In 1881 Hopkinson[3] proposed to utilize the self-induction of a coil, with iron core, to "choke" the currents of an alternate-current system instead of introducing wasteful resistance. In the same year a very important patent was taken out by MM. Marcel Deprez and J. Carpentier[4] for a system for the economical transport of electric energy by means of transformers. At the generating station the alternating currents of low potential were to be transformed by means of an induction-coil to currents of high potential, which could then be economically conveyed to a distance through long thin conducting-wires, and there, entering the fine wire primary coil of another transformer could be transformed down to low potential suitable for the lamps or motors. In 1882, Gravier[5] suggested the motor-dynamo as a transformer for continuous currents, a suggestion which had been partially anticipated by Sir W. Thomson[6] and by Gramme.[7] This suggestion was generalized in 1883 by Cabanellas,[8] and systems of distribution on the same plan were independently proposed by Edison,[9] and by Lane-Fox.[10] In 1882, Gaulard and Gibbs[11] revived the use of alternate-current distribution by induction-coils; their first patent proposes a coil of Ruhmkorff type. Their second patent[12] states that in their invention the alternate current in the primary circuit was to be maintained of constant strength, while its electromotive-force was varied, according to the demand on the secondary circuits. This implies distribution in series; in the same year they revived the construction of induction-coils with sheet-copper conductors set edge-on to the core under the name of "secondary generators." In 1883, Kennedy used a modified Gramme ring as a transformer; and in 1885, Deri and Zipernowsky[13] proposed the use of transformers for effecting the self-regulation of the alternate-current dynamo, and revived the use of induction-coils having laminated and closed magnetic circuits. In the same year Ferranti[14] brought out transformers constructed of iron strips.

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[1] *Experimental Researches*, i. 7, 1831.

[2] *Ann. Chim. Phys.*, lxvi. 5, 1837; and iv. 129, 1842.

[3] *Pogg. Ann.*, xxxiv. 185, 500, 1835.

[4] *Annals of Electricity*, v. 349, 1840; vii. 322, 1841.

[5] *Pogg. Ann.*, xlix. 72, 1840; lvi. 251, 1842.

[6] *Ibid.*, lxxxv. 465, 1851; and xcvi. 366, 1855.

[7] *Ibid.*, xlviii. 95, 1839.

[8] See Wiedemann's *Lehre von der Elektricität*, iv. 339.

[9] *Phil. Mag.*, xiv. 239, 480, 1857.

[10] *Comptes Rendus*, xxxvi. 649; and xxxvii. 801.

[11] Specification of Patent, 3059 of 1856.

[12] *Ibid.*, 1996 of 1877.

[13] *Ibid.*, 4212 of 1878.

[14] *Ibid.*, 4611 of 1878.

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[1] Specification of Patent, 5183 of 1878.

[2] *Ibid.*, 5257 of 1878.

[3] *Ibid.*, 3362 of 1881.

[4] *Ibid.*, 4128 of 1881.

[5] *Ibid.*, 1211 of 1882.

[6] *Rep. Brit. Assoc.*, 1881.

[7] *Comptes Rendus*, Nov. 23, 1874.

[8] *La Lumière Électrique*, iii. 44, and iv. 206, 1883; and Specification of Patent, 2880, 1885.

[9] Specifications of Patents, 3752 and 3949 of 1882; and U. S. Patents, Nos. 266,793, Oct. 31, 1882; 278,418, May 29, 1883; and 287,516, Oct. 30, 1883.

[10] Specification of Patent, 3692 of 1883.

[11] *Ibid.*, 4362 of 1882; and *La Lumière Électrique*, xiv. 40, 156, 1884.

[12] *Ibid.*, 2858 and 3173 of 1884.

[13] *Ibid.*, 3379 and 5201 of 1885.

[14] *Ibid.*, 15,251 of 1885.

Kennedy[1] had proposed to make the distribution at a constant potential, a method which has been adopted by Zipernowsky, Ferranti, and subsequently by Gaulard and Gibbs, and by Westinghouse in the United States, and which is nearly self-regulating. Improvements in details of construction have been made by Kapp[2] and Snell, Mordey, Westinghouse, and Statter. Swinburne has advocated the use of open-circuit transformers as less wasteful of energy at light loads. Recent improvements in motor-generators are due to Scott and Paris,[3] R. P. and J. S. Sellon,[4] and J. Swinburne,[5] the latter of whom suggests machines adapted for transforming from a circuit supplied at constant current to a secondary circuit fed at constant potential.

SYSTEMS OF DISTRIBUTION BY ALTERNATING TRANSFORMERS.

These are briefly two in number:—(1) *At constant potential*, the distributing mains branching to the various local points where the transformers supply the lights at low pressure. In this case the primary wires of the local transformers are coils of fine wire of many turns, and are all in parallel across the mains; the secondary coils being of thick wire and of few turns. (2) *With constant current*, the single main circuit going from the primary of one transformer to that of the next. In this case, as the primary wires are in series, they are thicker and of few turns. The first of these systems is suitable for incandescent lighting, the second for arc lighting.

GENERAL PRINCIPLES OF ALTERNATING TRANSFORMERS.

An alternating transformer may be regarded as a species of dynamo, in which neither armature nor field-magnet revolve, but in which the magnetism of the iron circuit is made to vary through rapidly repeated cycles of alternation, by separately exciting it with an alternating current. The primary coil of the transformer corresponds to the field-magnet coil of the dynamo; the secondary of the transformer to the armature coil of the dynamo.

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[1] *Electrical Review*, xii. 486, June 9, 1883.

[2] *Journal Soc. Teleg. Engineers*, xvii. 96, 1888.

[3] Specification of Patent, 6260 of 1884.

[4] *Ibid.*, 3525 of 1885.

[5] *Ibid.*, 6682 of 1887.

Many of the rules for construction of dynamos apply with equal force to the construction of transformers; for example, the rules concerning insulation, lamination of iron cores, and the like. In all cases where transformers are used with very high potentials, the utmost care must be taken about the complete and efficient insulation of all the wire (and connexions) of the high-pressure coils: it should on no account be wound in alternate layers between the windings of the low-pressure circuit, nor stranded with it into a cable; it should, while properly enclosing the iron circuit, not only be as perfectly insulated, but as completely isolated as may be from the low-pressure wire and from all other metal work in the transformer.

In the alternating transformer, by whatever name called, the function of the iron core is to carry the magnetic lines of force (that are created by the current in the primary coil) through the convolutions of the secondary coil. The rate at which the magnetic lines due to the primary current are cut by the secondary circuit is the measure of the electromotive-force given to the secondary circuit. In order to be able to calculate the amount of cutting of magnetic lines that goes on with various strengths of primary current and various rates of alternation, it is convenient to know the amount of cutting of magnetic lines that takes place when unit current is made to flow, or is stopped in the primary coils. Let M be used as a symbol for this quantity. It will be proportional to the number of turns in the secondary coil, because each turn encircles the iron core and cuts the magnetic lines; it will also be proportional to the number of turns in the primary coil, because, *cæteris paribus*, the magnetism evoked in the iron core is proportional to the ampere-turns that excite it; it will also be proportional at every stage to the permeability of the iron core. We may, in fact, calculate M by the magnetic principles laid down in Chapter VI. Suppose the iron core to form a closed circuit of length l, section A, permeability μ; and that S_1 and S_2 are the respective numbers of turns in primary and secondary. Then, if the primary current is unity (in absolute C.G.S. units), the magnetomotive-force due to it will be $4\pi S_1$, and the magnetic resistance will be $l/A\mu$. Dividing the former by the latter, we shall have an expression for the number of lines in the core; this multiplied by S_2 gives the amount of cutting of lines by the secondary circuit; or in symbols

$$M = 4\pi S_1 S_2 A\mu/l.$$

The name given to this quantity is the *coefficient of mutual induction.* If the current in the primary have the value i_1 (absolute C.G.S. units), then the amount of cutting by the secondary on turning this current on or off will be $M i_1$. And if the rate of increase or decrease of the primary current at any instant is known, this multiplied by M will give the electromotive-force impressed at that instant on the secondary circuit. Now it is obviously advantageous in a transformer that this quantity should be as great as possible, for it is desirable to attain the requisite electromotive-force in the secondary with as little primary current as possible. The conditions are, however, a little conflicting: S_2 must not be made large, on account of internal resistance and cost of copper; but it is clear that a compact magnetic circuit, having l small, A large, and the iron of good quality, will be of advantage. In the particular case (for series working), where the primary and secondary wires are to carry equal currents, it is clear that for a given total weight of copper, the maximum product $S_1 S_2$ will be afforded when there are equal numbers of turns in the coils, and therefore equal weights of copper. In other cases, provided the wires are proportioned to the currents they have to carry, and that equal heat can be developed in each coil, equal weights of copper is still a good rule, though the numbers of turns in the two coils will be widely different. It has been assumed that there is no magnetic leakage; that all the lines of force created in the core pass through the secondary coils. This assumption is very nearly fulfilled in those transformers in which the magnetic circuit is effectively closed upon itself.

The next important point is that the magnetic lines of force created by the primary current in the core pass through the convolutions of the primary coil itself, and that therefore there will be self-induced electromotive-forces in the primary coil, which will tend to oppose the impressed variations of current. Considerations precisely analogous to those above will show that there will be a *coefficient of self-induction*, which we will call L_1, which represents the amount of cutting, by the primary coils, of the magnetic lines created in the coil when the primary coil carries unit current; and we may calculate, on magnetic principles, as before, the value of this coefficient to be

$$L_1 = 4\pi S_1^2 A \mu / l. \qquad L_1 = \frac{4\pi S_1}{l}$$

That is to say, L_1 will be large in proportion to the goodness of the magnetic circuit; and (as in the case in transformers for distribution at constant pressure) as S_1 is itself large, L_1 will be enormous. As will presently be seen, this has important results in the automatic action of transformers.

The electromotive-forces induced (by the variations of magnetization of the core) in the secondary circuit will, of course, produce no currents if the secondary circuit is open; but if the secondary circuit is closed there will be currents, the strength of which will depend also upon the resistances and upon the counter electromotive-forces (if any) in this circuit. But these secondary currents, as they circulate around the convolutions of the secondary coil, exercise a magnetizing (or rather a demagnetizing) action, the effect of which on the core will depend not simply upon their strength, but also upon their phase. When the transformer is doing full work, the secondary current is rising in the positive sense, almost exactly as the primary is rising in the negative direction, their phases being almost exactly in opposition. That is to say, at full work the secondary current will exercise a great demagnetizing action. The total magnetizing force[1] at work is equal to $4\pi (S_1 i_1 + S_2 i_2) \div 10$, where the proper signs + and – must be assigned to i_1 and i_2 according to the sense in which they circulate around the core. Further, there will be a coefficient of self-induction L_2 in the secondary circuit, such that

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[1] See p. 176.

$$L_2 = 4\pi S_2^2 A \mu / l.$$

$$L_2 = \frac{\frac{14\,\pi\,S_1}{l}}{A\mu}\,\Big|\, S$$

As will be seen later, there is an inter-action between the primary and secondary circuits, owing to mutual induction, tending to neutralize the effects of self-induction in both circuits.

In a well-built transformer it is clear that

$$M = \sqrt{L_1 L_2}.$$

If, however, all the magnetic lines due to one circuit are not enclosed by the other, M will have a less value than is indicated by the above relation.

The relation between the two electromotive-forces and the two sets of windings is readily stated in a way sufficiently accurate for ordinary purposes, by saying that the ratio of the two electromotive-forces is equal to that of the windings, or

$$\frac{E_1}{E_2} = \frac{S_1}{S_2} = p.$$

The number p which represents the ratio of the windings we shall call the *coefficient of transformation.*

If it is assumed that there are equal weights of copper used in the primary and secondary coils, then the following relations will hold good :—

	Primary.	Secondary.	Ratio.
Windings	S_1	S_2	p
Resistance	r_1	r_2	p^2
Self-induction	L_1	L_2	p^2
Electromotive-force	E_1	E_2	p
Current	i_1	i_2	p^{-1}
Heat-waste	$i_1^2 r_1$	$i_2^2 r_2$	1

Also

$$M = \frac{L_1}{p} = p L_2.$$

It must be always remembered that the symbol E is used above for the virtual or square-root-of-mean-square value of the alternating electromotive-force: the actual value of E at any moment being represented by the expression $E = D \sin 2\pi n t$; where D is the maximum value to which E rises, and is equal to $2\pi n S N$ (see p. 626), n being the number of alternations per second. Further, for alternate-currents (see p. 629) Ohm's law must be written as

$$i = \frac{D \sin (2\pi n t - \phi)}{\sqrt{R^2 + 4\pi^2 n^2 L^2}}.$$

We are now able to find a more exact expression for the induced electromotive-force in the secondary circuit, for the number of magnetic lines induced by the primary circuit into the core (when there is no current in the secondary) is $M i$; and therefore

$$E_2 = - M \frac{di}{dt} = M \frac{2\pi n D \sin\left(2\pi n t - \phi - \frac{\pi}{2}\right)}{\sqrt{r_1^2 + 4\pi^2 n^2 L_1^2}};$$

or, writing $2\pi n = \omega$, we have (neglecting phase, and considering magnitude only)

$$E_2 = \frac{\omega M}{\sqrt{r_1^2 + \omega^2 L_1^2}} E_1;$$

or, putting $$\frac{\omega M}{\sqrt{r_1^2 + \omega^2 L_1^2}} = k,$$

$$E_2 = k E_1.$$

Examining the expression k, it will be seen that if r_1 is small compared with ωL_1, as will be the case where there are very rapid alternations and plenty of iron in the core, k will be equal to M/L_1, or will be the reciprocal of p, and equal to $S_2 S_1$.

By leaving out of consideration differences of phase in the above argument, it must not be supposed that these differences of phase are small. On the contrary, they may be very large. If, however, assuming E_1 to be a sine-function, we remember that the average value of the square of the sine (between 0° and 360°) is equal to $\frac{1}{2}$, then we shall have the virtual primary volts E_1 equal to D divided by $\sqrt{2}$. It is in this sense (namely, taking the square-root of mean square as the basis for comparison) that we may say that E_2 is to E_1 in the same ratio as S_2 to S_1, or that the ratio of the primary and secondary volts is equal to the ratio of the primary and secondary windings. If the two windings are properly wound over the core so that there is no magnetic leakage, then the variations of magnetism of the core will set up in the two windings electromotive-forces that are precisely proportional to the respective number of turns. In the primary winding this electromotive-force will oppose that which is supplied from without. If, following the notation used for motors, we call $\mathcal{E}_1$ the volts supplied to the primary terminals, $\mathcal{E}_1$ will be greater than E_1 by an amount dependent on the internal resistance and current in the primary. Similarly, the volts at the secondary terminals e_2 will be less than E_2 by an amount dependent on the internal resistance of the secondary winding and on the secondary current. In any case, the work given out (per second) by the secondary will be very nearly equal to the work imparted to the primary; the difference being the loss due to the production of eddy-currents, and the waste work spent in carrying the residual magnetization of the iron through repeated cycles of alternation. If $\mathcal{E}_1 i_1$ be the watts imparted to the primary, and $e_2 i_2$ those given out by the secondary, it is found that $e_2 i_2$ may be as much as 97 per cent. of $\mathcal{E}_1 i_1$. A current of 10 amperes at 2000 volts imparted to a good transformer, having twenty times as many turns on its primary as it has on its secondary coil, will be transformed by the secondary into a current of 200 amperes[1] at very nearly 100 volts.

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[1] It must be remembered by beginners that the gain in quantity of current is balanced by the diminution in electromotive-force; otherwise the work would not be equal. It is a curious fact in the history of invention that in 1883 the United States Patent Office refused to grant a transformer patent to Mr. Bernstein on the ground that he could not possibly get a larger quantity of current out of the

One of the most difficult points for beginners to comprehend in the action of transformers is the way in which, when used in parallel distribution, they of themselves adjust the amount of primary current that flows through them from the mains. Suppose a transformer, having a primary coil of many turns of fine wire to receive a current of 1 ampere from mains at, say, 2000 volts, and having a secondary coil adapted to give out a current of 20 amperes at 100 volts. This would supply 40 lamps, each taking a ½-ampere of current. When all the lamps are on, the 20-ampere flows through the secondary, and the 1-ampere flows through the primary. If now half the lamps are turned out, only 10 amperes will be supplied by the secondary, and now only half an ampere is wanted from the mains to flow through the primary. As a matter of fact, under these circumstances, the current supplied through the primary automatically diminishes in the proper proportion. As lamp after lamp is turned out in the secondary circuit, so, little by little, the primary current also diminishes; when all lamps are out, and the secondary circuit is completely opened, the primary current is found to have of itself all but stopped, although the mains are still supplied at full pressure. Nothing has been done to the primary circuit: there is still a perfect path through which the current might flow, no resistance has been inserted in the primary coil, yet the current does not flow to any extent through it. The clue to the matter lies in the inductive reaction of the iron core. As the waves of primary current circulate around the core, they set up periodic magnetizations in the iron; but the periodic fluctuations of the magnetism of the iron necessarily set up electromotive-forces in the surrounding coils. If, in a short time dt, the change that takes place in the number of magnetic lines in the core is $d\,\mathrm{N}$, then during that short time the electromotive-force induced in a wire which is coiled S times round the core will be equal to $\frac{d\mathrm{N}}{dt}$ (this number should be divided by 10^8 to bring to volts). The electromotive-force in the secondary

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secondary than was supplied to the primary. Nevertheless, the same Patent Office in 1886 issued a patent to Gaulard and Gibbs for this very thing!

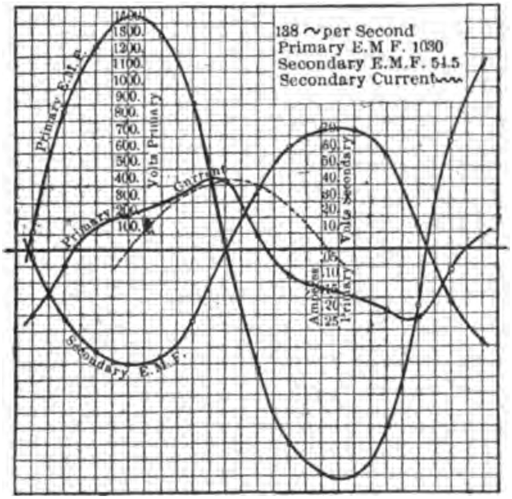
coil will be $S_2 \frac{dN}{dt}$; and there will of course be also another electromotive-force induced in the primary equal to $S_1 \frac{dN}{dt}$. Now it is this self-induced counter electromotive-force in the primary which dams back the currents from the mains when the secondary circuit is open. The variation of the magnetism of the core always tends to set up electromotive-forces opposing change. It does this in two ways. If there is no secondary it sets up back electromotive-forces in the primary which dam back the current. If there is a secondary wire present it sets up currents in the secondary in a sense opposite to those of the primary. Consider what happens when there are no lamps on: the secondary circuit is entirely idle, and takes no part in the action. The alternating electromotive-force of the mains impresses alternating currents in the primary coil, which in turn impress an alternating magnetization on the core, and this finally induces alternating electromotive-forces into the primary circuit, tending to stop the primary currents. The greater the variation of magnetization of the core, the greater the induced electromotive-force. Now consider what happens when the lamps are on. There will be considerable currents in the secondary: these are always in almost exactly opposite phase to the primary currents. When the primary current is increasing, the secondary current is increasing negatively, that is to say, is increasing whilst circulating round the core in the opposite sense to the primary. The magnetizing tendency is of course proportional to the difference between the ampere-turns of the primary and those of the secondary. [It is, as previously stated, equal to $4\pi(S_1 i_1 + S_2 i_2) \div 10$, the proper signs being assigned to the currents according to their sense.] If, as is the usual case, the secondary volts are maintained nearly constant, it follows that the cycles of magnetization, and therefore the nett magnetizing forces, are nearly the same at all loads. It would therefore appear as though the back electromotive-force tending to dam back the primary current ought to be the same at all loads. But this we know is not true. The explanation lies in the phase-relations: for, at light loads the counter electromotive-force in the primary is almost exactly in opposite phase to the primary impressed electromotive-force, whilst at full load it is nearly in quadrature with the latter. To put it into other words, as lamps are turned on in the secondary and more secondary current flows, the increased mutual induction virtually wipes out the self-induction in the primary circuit, and the effective back-electromotive-forces in the primary coil, which in the first case dammed back the current from the mains, are less; hence more current flows in the primary.

Graphic constructions illustrating the variations of phase and magnitude of the electromotive-forces and currents have been given by Kapp, Blakesley, and Fleming. If the impressed $\mathcal{E}_1$ is constant, then the magnetization is of course carried to the greatest degree when the transformer is working on open circuit. If, however, the system is so regulated or over-compounded as to keep up a constant pressure at the lamps, then the magnetization of the cores is a maximum at full load. It is expedient to arrange that there shall be so much iron in the core that the induction in it need never be carried above 6000 or 7000 lines to the square centimetre. It is possible to work above these values, but the transformer emits a singing noise, and the iron grows hot. Work is, of course, spent in carrying the iron to a high degree of magnetization. Of this work, the greater part is returned to the secondary circuit during the next part of the cycle as the magnetization of the iron descends; but part, namely, that spent in producing the so-called permanent portion of the magnetization, is lost, being frittered down into heat. As to the phases of the various waves, as mentioned above, the secondary current is always in almost exactly opposite phase to the primary current; and the secondary electromotive-force is in almost exactly opposite phase to the primary electromotive-force. But the difference of phase between E_1 and i_1 varies greatly with the work done. When there are no lamps on, and no secondary current, i_1 is small, and its phase differs by very nearly 90° from that of E_1: as lamps are switched on and i_2 grows, i_1 grows also, and the angle of lag between E_1

and i_1 grows less. The phase of the magnetization of the core (which is always necessarily 90° in advance of the phase of E_2) is always[1] very nearly 90° behind the phase of E_1.

The actual performance of transformers has been carefully examined by Prof. H. J. Ryan,[2] who has plotted out curves to show the forms and phases of the several varying quantities. The transformer used was a small one of 600 watts capacity adapted for transforming down from 1000 to

FIG. 468.



TRANSFORMER CURVES ON OPEN CIRCUIT.

50 volts, the number of windings being 675 in the primary, and 35 in the secondary coil. The volume of laminated iron was about 2050 cubic cm. The mean length of the magnetic circuit was 30·8 cm. and mean cross section 63·3 sq. cm.; the frequency used was 138. Figs. 468, 469, and 470 show the results. It will be noted that although the primary

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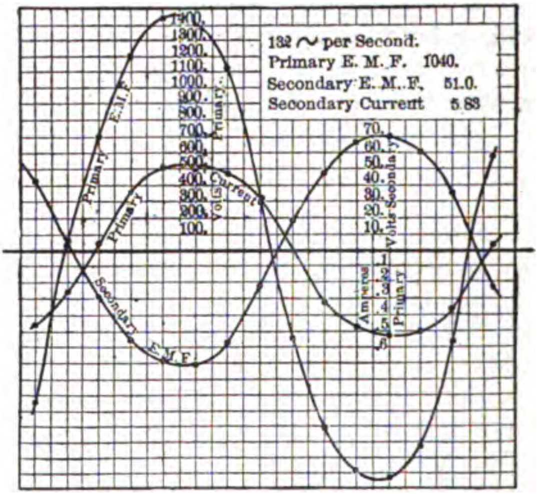
[1] See experiments by Major Cardew, in *Electrical Engineer*, July 1887, p. 358.

[2] *Amer. Inst. Electrical Engineers*, 1889 and 1890. See also *Electrical World*, xiv. 419, Dec. 28, 1889, and xvi. 10, July 25, 1890; also *The Electrician*, xxiv. 263, and xxv. 313, 1890; also *La Lumière Électrique*, xxxv. 233, 1890. See also an appendix paper by Messrs. Humphrey and Powell in *Electrical World*, xvi. 11, 1890, and *The Electrician*, xxv. 280, 1890.

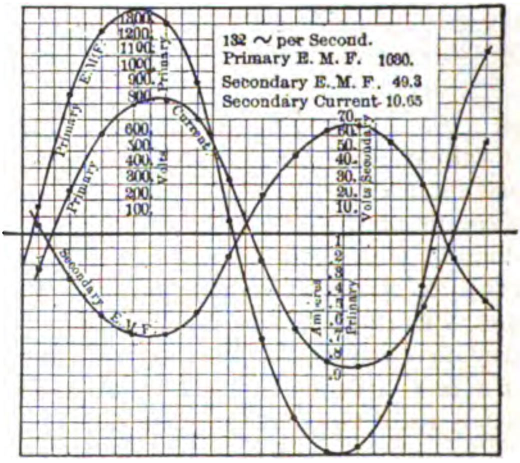
current curve differs widely from a curve of sines (especially at light loads), nevertheless the curve of secondary volts is much

FIG. 469.



TRANSFORMER CURVES AT HALF LOAD.

FIG. 470.



TRANSFORMER CURVES AT FULL LOAD.

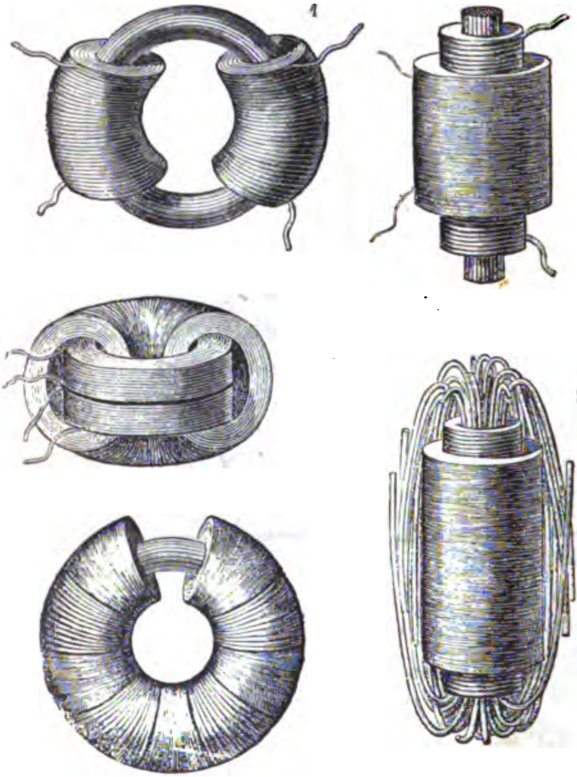
more nearly like a sine-curve; and it is always in almost exact opposition of phase to the curve of primary volts. In

Ryan's paper are many valuable remarks, not the least important being a passage in which he points out that leakage of magnetism not only diminishes the mutual induction, but increases the self-induction of each circuit, and therefore tends to cause a lag in both the currents. In a second paper, Prof. Ryan shows that the loss of energy by eddy-currents in the core is less when the core is hot than when it is cold.

CONSTRUCTION OF ALTERNATING TRANSFORMERS.

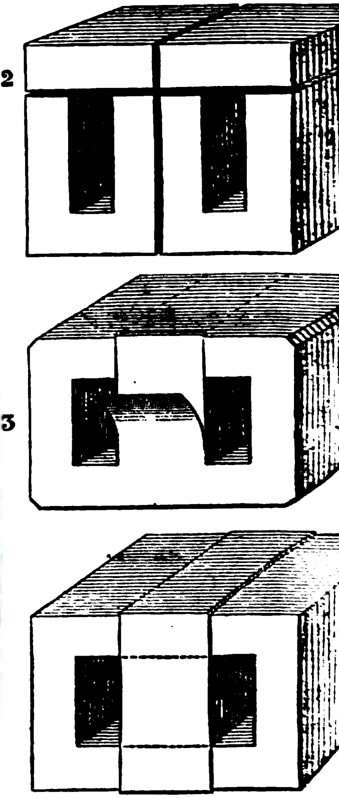
All transformers consist of a core of iron, around which the primary and secondary coils are so wound that the core carries the magnetic lines from the one set of coils through the other. Faraday's first induction-coil, No. 1 in Fig. 471, is thoroughly typical of the principle common to all transformers. In Faraday's actual ring the iron was not laminated. No. 2 of Fig. 471 is the cylindrical type of induction-coil introduced by Masson and Ritchie, and perfected for spark purposes by Ruhmkorff. No. 3 depicts the form given to the transformer by Varley for telegraphic purposes. The core of iron wires is made long, and the ends are bent over so as to constitute practically a closed magnetic circuit. The Ferranti transformer resembles this, but has the core of narrow strips of sheet iron. A similar form has been used recently by Gaulard and Gibbs. No. 4 is a form introduced by Zipernowsky; in this the primary and secondary coils are laid upon one another, and the iron core is then wound through and over them by a shuttle, so that the whole of the copper is enclosed within the iron. In the drawing of Nos. 3 and 4 the front portion of the iron winding is represented as removed to show the interior. Mr. Kapp has proposed the name of "shell-transformers" for this type of apparatus as distinguished from those with a mere straight or a non-expanded internal core. No. 5, which is also a form due to Zipernowsky, is constructed somewhat like a Gramme ring. There is an iron wire ring core, upon which the copper coils are wound in sections, but with alternate sections connected together, one set as primary the other as secondary. In the drawing, one of the ten sections is represented as removed to show the core. Nos. 6, 7, and 8 represent three closely allied methods of procuring the necessary structure of laminated iron, the parts in these instances being stamped from sheet iron. The copper coils are not shown in these three, but in each they consist of two sets of windings, previously wound on rectangular formers of such a form as to admit of insertion into the iron stampings. In No. 6, which shows the method of Kapp and Snell, there are two sets of U-shaped stampings, set side by side, forming two parallel channels to receive the coils. The stampings that

FIG. 471.



VARIOUS TYPES OF ALTERNATING TRANSFORMERS.

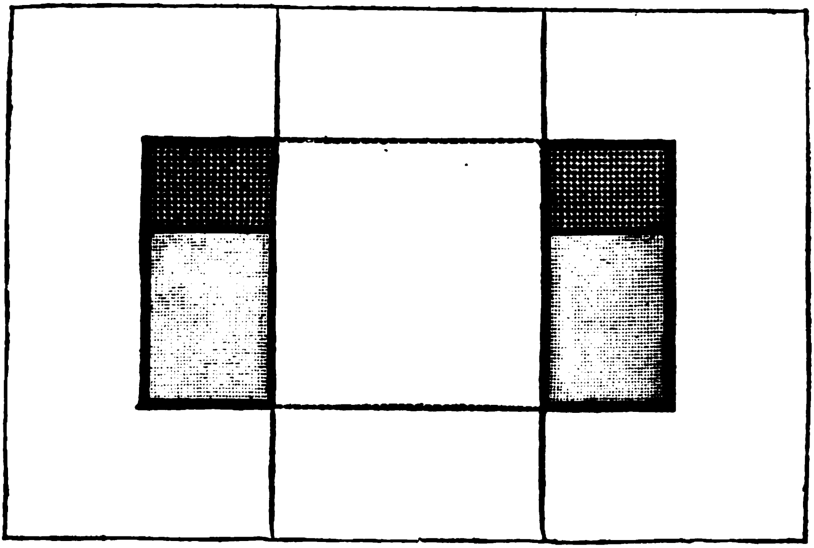
FIG. 472.



CORE-PLATES OF TRANSFORME

are removed between the limits of the U pieces serve to complete the magnetic circuits above. No. 7 is the form adopted by Westinghouse. The stamping in this form must be bent up in order to slip it on over the coils; the core being put together over the coils. With Mordey's form, No. 8, the piece which is removed from the interior of the rectangular stamping is placed across it (after having been covered on one side with paper as insulation), the outer rectangular stampings being passed over the outside of the coils, and the cross-pieces slipped in between them, thus avoiding waste of material, and securing a good magnetic circuit with ample ventilation. Fig. 473 shows the exact proportions of the stampings of Mordey's transformer, including a section of the coils. The newest form of this apparatus, which is constructed by the Brush (Anglo-American) Company, is further depicted in Figs. 474, 475.

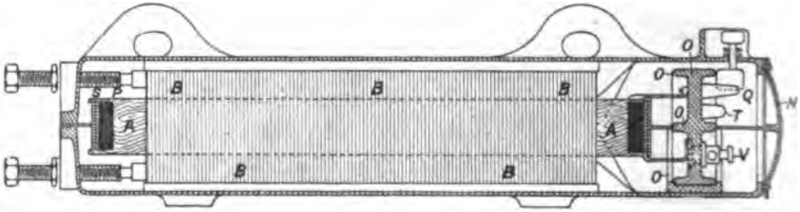
FIG. 473.



MORDEY'S TRANSFORMER (Section).

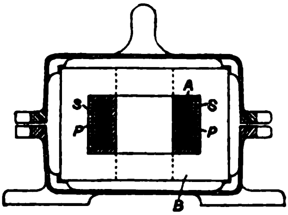
As an example, the following dimensions are given for a transformer capable of transforming a current of 1·5 ampere at 1000 volts down to a current of 37·5 amperes at 40 volts. Total external size, 20 × 6 × 4 inches; $S_1 = 300$; $S_2 = 12$; $r_1 = 10$ ohms; $r_2 = 0·014$ ohms; gauge of primary wire, 0·035 inch; secondary wire 25 in parallel, each 0·12 inch gauge; weight of copper in coils, about 5 lbs. in primary and 5½ lbs. in secondary; weight of iron used, about 50 lbs.; efficiency, 97·2 per cent.

FIG. 474.



MORDEY'S TRANSFORMER (Section).

FIG. 475.



MORDEY'S TRANSFORMER (Transverse section).

In this pattern the coils P and S are wound upon a light former A, made of hard wood steeped in ozokerit. The core-disks B are partly made of stampings resembling Fig. 473, interlaced, and partly of other stampings which fill up the interstices which would otherwise be left between the superposed pieces. By this means the leakage of the magnetic circuit is reduced to a negligible amount. The whole is secured in a cast-iron cover made water-tight by a packing of rubber. The connexions, switch, and safety-fuses are mounted on a porcelain block O, in the end of the chamber.

Fig. 476 illustrates the so-called "hedgehog" transformer of Swinburne,[1] having as core a bundle of iron wires which, after receiving the copper coils, are spread out at their ends so as to reduce the magnetic reluctance, which is in any case great, the magnetic circuit being an open one.

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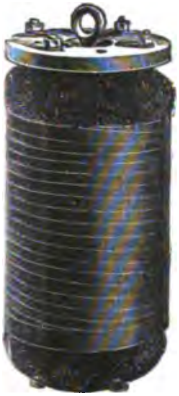
[1] *Journal Inst. Electr. Engineers*, xx. 183, 1891.

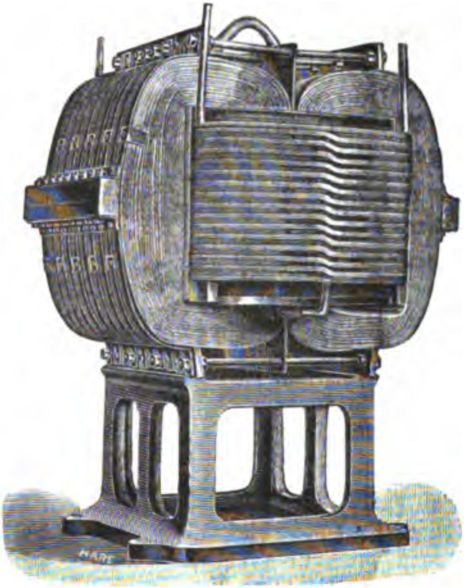
Ferranti's transformer (Fig. 477) for extra high pressure work has a core made of a large number of thin strips of iron, which pass vertically up through the middle of the copper coils, and are bent round below and above on each side and interlapped so as to complete the magnetic circuit. The coils are made of copper-strip, very carefully insulated, and compacted together in sections by insulating material. There are three coils thus built up, the innermost being a portion of the primary, outside this the secondary, and outside this again the rest of the primary. Sheets of ebonite are interposed in the spaces between these coils so as to prevent sparking across from the high-pressure coils. There is also room for air ventilation in the vertical spaces where these sheets of ebonite are wrapped round between the three piles of coils.

FIG. 476.



SWINBURNE'S HEDGEHOG TRANSFORMER.

FIG. 477.



FERRANTI'S TRANSFORMER.

With most of the preceding modes of construction the coils cannot be readily removed from the transformer, owing to the mode of putting together the iron parts. A more accessible structure is that designed by C. E. L. Brown, in which the coils are wound on a cylindrical tube of insulating material through which can be inserted a core made up of laminæ of different widths, almost filling the tube, and projecting squarely at its ends. The magnetic circuit is completed by means of U-shaped iron stampings assembled in two sets, one placed below, and the other above, which can be removed *en bloc*, so giving access to the coils. These transformers are immersed in oil.

Another construction, which also gives ready access to the coils, is the design of Mr. Kapp depicted in Plate XXIX. Here the coils, primary and secondary, are wound on ebonite bobbins, which slip over a long rectangular core made up of plates. To complete the magnetic circuit other assemblages of core plates of equal length are carried parallel to the core, above and below, and the four spaces at the ends are filled by four blocks of small stampings assembled together. The whole is secured in a substantial frame and protected by an external cover of cast iron bolted down.

The advantages possessed by transformers which have closed magnetic circuits over those which have not are of various kinds; in particular they require a smaller exciting current for an equal magnetic cycle, so that there is less waste of energy in the copper, particularly on small loads. On the other hand, in the open-circuit transformers, owing to the self-demagnetizing action of non-closed iron cores, there is less waste of energy by hysteresis in the iron. This point has been strongly insisted on by Mr. Swinburne.[1] Some experiments made by Mr. Ferranti are suggestive. A number of iron strips were placed side by side and a coil wound upon them, the ends of the strips protruding far beyond the coil. This was used as a self-induction or choking coil at 100 volts, alternating at 66 periods per second: the number of watts expended by the current being a measure of the work required to carry the iron through the magnetic cycle needful to balance the impressed volts. When the strips were simply straight, the current was found to be 22 amperes, giving apparent watts 2200; but as the angle of lag was about 86° 30′, the true watts were only 135·5. Then the ends of the strips were spread out to imitate the hedgehog arrangement, with the result that to carry the iron core through the same magnetic cycle as before (or a slightly greater cycle) required only 10·75 amperes, with expenditure of 1075 apparent or 116·9 real watts. Lastly, when the ends of the strips were bent right round and laid between one another, completing the magnetic circuit as in the Ferranti transformer, the current fell to 0·9 ampere, indicating that a still higher degree of magnetization had been obtained with expenditure of only 90 apparent or 49·6 real watts.

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[1] Proc. British Association, 1889 (see *The Electrician*). See also an important series of articles by Mr. Sydney Evershed, on Design of Transformers in *The Electrician*, beginning vol. xxvi., p. 477.

Another point strongly in favour of closed circuit transformers is the entire absence of waste from eddy-currents in the copper conductors, however massive; for the magnetic lines seem to snap across them absolutely instantaneously, so that there is never any difference in the intensity of the magnetic field in which the two sides of a conductor find themselves.

The relative advantages of open and closed circuit transformers have been lately discussed in the Institution of Electrical Engineers.[1]

Tests of the efficiency of transformers have been given by Mordey,[2] Ayrton,[3] and others.

For further information on the constructional details of transformers the reader is referred to a series of articles by R. Kennedy, in the *Electrical Review*, xx. 247 and seq., 1887, since republished in separate form under the title *Electrical Distribution by Alternating Currents and Transformers*; to an article by Rechniewski, in *La Lumière Électrique*, xxvi. 95, 1887; to the paper by G. Kapp, in *Journal Soc. Teleg. Engineers*, xvii. 96, 1888, to which reference is made above; to the papers by Mr. Swinburne and by Mr. Evershed already alluded to; and to the volumes of Prof. Fleming on *The Alternate Current Transformer*, which appeared in serial form in *The Electrician* in the years 1889–91.

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[1] See *Journal Inst. Electrical Engineers*, xx. 183 to 251, 1891.

[2] *Ib.*, xviii. 609, 1890.

[3] *Ib.*, 664.

THEORY OF ALTERNATE TRANSFORMERS.

There are two ways of treating the theory of transformers—the first by introducing the notion of coefficients of mutual and self-induction into the differential equations for the two circuits; the second by considering the magnetomotive-forces at work in the iron core as the result of the algebraic sum of the ampere-turns in the two circuits, and deducing the electromotive-forces which result from the variations in the magnetic induction of the core—

First Method.

This method, introduced by Maxwell,[1] consists in finding the electromotive-force induced in the second circuit by the variations of current impressed upon the first circuit. Accordingly we write as the differential equation of the first circuit—

$$E_1 - M\frac{d\,i_2}{d\,t} - L_1\frac{d\,i_1}{d\,t} - R_1 i_1 = 0; \qquad (1)$$

where E_1 is the impressed electromotive-force of the dynamo, which is supposed to fulfil the condition $E_1 = D \sin 2\pi n t$ (see p. 626), and where L_1 and R_1 are the coefficient of self-induction and resistance of the primary circuit. If the supposition is admitted that a constant (alternating) potential can be maintained at the terminals of the primary coil (by proper compounding of the dynamo, see p. 747, or otherwise), then the letters E_1, L_1, and R_1, may be taken to apply to that part of the primary circuit only which lies between the terminals of the primary coil. From this differential equation we have to deduce a value for $M\frac{d\,i_1}{d\,t}$. For brevity we will write ω for $2\pi n$; and $-\omega^2 i$ for $\frac{d^2 i}{d t^2}$, because i is a sine-function. Then differentiating equation (1) we get—

$$\frac{d\,E_1}{d\,t} + M\omega^2 i_2 + L_1\omega^2 i_1 - R_1\frac{d\,i_1}{d\,t} = 0. \qquad (2)$$

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[1] *Philosophical Transactions*, clv. pt. i. p. 459, 1865. In this paper Maxwell shows that the effect of the second circuit is to add to the apparent resistance and diminish the apparent self-induction of the first circuit. The student will find the equations more fully treated by Mascart and Joubert, *Électricité et Magnétisme*, i. 593, and ii. 834; also by Hopkinson, *Journal Soc. Teleg. Engineers*, xiii. 511, 1884; Ferraris, *Mem. Accad. Sci.* (Turin), xxxvii. 1885; and by Vaschy, *Annales Télégraphiques*, 1885–6, or *Théorie des Machines Magnéto et Dynamo-électriques*, p. 31. A summary of Maxwell's work is given in Fleming's book.

Now multiply this by R_1 to get equation (3), and multiply equation (1) by $L_1\omega^2$, to get equation (4); and add (3) and (4) to get (5).

$$R_1\frac{dE_1}{dt} + M\omega^2 R_1 i_2 + L_1\omega^2 R_1 i_1 - R_1^2\frac{di_1}{dt} = 0, \qquad (3)$$

$$L_1\omega^2 E_1 - L_1\omega^2 M\frac{di_2}{dt} - L_1^2\omega^2\frac{di_1}{dt} - L_1\omega^2 R_1 i_1 = 0, \qquad (4)$$

$$\left(R_1^2 + L_1^2\omega^2\right)\frac{di_1}{dt} = R_1\frac{dE_1}{dt} + L_1\omega^2 E_1 + M\omega^2\left(R_1 i_2 - L_1\frac{di_2}{dt}\right). \qquad (5)$$

Now multiply every term by $\frac{M}{R_1^2+L_1^2\omega^2}$, and write the following abbreviations:—

$$\frac{M\omega}{\sqrt{R_1^2+L_1^2\omega^2}} = k,$$

$$k^2 R_1 = \rho,$$

$$k^2 L_1 = \lambda,$$

$-\frac{k^2}{M}\left(\frac{R_1}{\omega_2}\cdot\frac{dE_1}{dt} + L_1 E_1\right) = E_2 = k E_1 \sin(\omega t - \phi)$, where ϕ relates to the phase of the electromotive-force; and we may write equation (5) as—

$$M\frac{di_1}{dt} = \rho i_2 - \lambda\frac{di_2}{dt} - E_2. \qquad (6)$$

Now the differential equation for the second circuit is—

$$M\frac{di_1}{dt} + L_2\frac{di_2}{dt} + R_2 i_2 = 0; \qquad (7)$$

there being in this circuit no other electromotive-forces than those due to mutual and self-induction. Inserting in (7) the value obtained in (6), we get as the final equation—

$$(R_2 + \rho)\, i_2 + (L_2 - \lambda)\frac{di_2}{dt} - E_2 = 0. \qquad (8)$$

This shows us that the whole effect is equivalent to that which would happen if, the primary circuit being absent, there were introduced into the secondary circuit an electromotive-force equal to $k E_1$, and at the same time the resistance were increased by a quantity equal to $k^2 R_1$, and the self-induction were diminished by a quantity equal to $k_2 L_1$. Further, examination of k shows us that if the frequency of alternation and the permeability of the iron core be great enough, k becomes equal to $M \div L_1$, or equal to the reciprocal of p, the ratio of the primary and second windings. But if there are equal weights of copper in the two coils, $L_1 = p^2 L_2$ and $R_1 = p^2 R_2$. So that the effect, when the transformer is fully at work, is to make $\lambda = L_2$, and $\rho =$ the resistance of the secondary coil; or self-induction is wiped out, and the internal resistance of the secondary is virtually doubled.

Second Method.

In this method, due to Hopkinson,[1] we begin by considering the magnetomotive-force requisite to force N magnetic lines through a core having length l and permeability μ. This magnetomotive-force is due to the algebraic sum of the ampere-turns in the two coils. Following the argument on p. 177, Chapter VI., we may therefore write:—

$$\frac{4\pi}{10}\left(S_1 i_1 + S_2 i_2\right) \div \frac{l}{A\mu} = N; \qquad (1)$$

or if the core has area of cross-section A, and there are B lines to the square centimetre, we may write $N = A\,B$; and then, the magnetomotive-force will be—

$$\frac{4\pi}{10}\left(S_1 i_1 + S_2 i_2\right) = A\,B\frac{l}{A\mu} = \frac{B}{\mu}\,l = H\,l. \qquad (2)$$

We then write two equations for the electromotive-forces impressed in the two circuits as follows:—

$$\begin{cases} E_1 = R_1 i_1 - S_1\dfrac{dN}{dt} = R_1 i_1 - S_1 A\dfrac{dB}{dt}, & (3) \\ 0 = \left(r_2 + R_2\right) i_2 - S_2\dfrac{dN}{dt} = \left(r_2 + R_2\right) i_2 - S_2 A\dfrac{dB}{dt}; & (4) \end{cases}$$

where R_2 is the resistance of the lamp circuit, and r_2 the internal resistance of the secondary oil. Multiplying (3) by S_2 and (4) by S_1, we deduce—

$$S_2 E_1 = S_2 R_1 i_1 - S_1 (r_2 + R_2) i_2;$$

which with equation (2) gives—

$$i_1 \{S_2^2 R_1 + S_1^2 (r_2 + R_2)\} = S_2^2 E_1 + S_1 (r_2 + R_2)(10\,H\,l \div 4\pi),$$
$$i_2 \{S_2^2 R_1 + S_1^2 (r_2 + R_2)\} = -S_1 S_2 E_1 + S_2 R_1 (10\,H\,l \div 4\pi);$$

and

$$A\frac{dB}{dt} = -\frac{(r_2 + R_2) S_1 E_1}{S_2^2 R_1 + S_1^2 (r_2 + R_2)} + \frac{10\,H\,l}{4\pi}\cdot\frac{R_1 (r_2 + R_2)}{S_2^2 R_1 + S_1^2 (r_2 + R_2)} \qquad (5)$$

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[1] *Proc. Roy. Soc.*, February 1887.

The second term may be neglected simply because $H\,l$ is small compared with $\frac{4\pi}{10}\,S_1\,i_1$; in other words, because it is only the difference between $S_1\,i_1$ and $S_2\,i_2$ (both of which are very large), that is needed as a magnetomotive-force, and this is small if the permeability of the iron is great as it is when, as in actual practice, B is not carried above 8000 or 10,000 lines to the square centimetre. We have then—

$$A\frac{dB}{dt} = \frac{dN}{dt} = -\frac{(r_2 + R_2)\,S_1\,E_1}{S_2^2\,R_1 + S_1^2\,(r_2 + R_2)}.$$

And remembering that $E_2 = S_2\,\frac{dN}{dt}$, we get

$$E_2 = -\frac{(r_2 + R_2)\,E_1\,\frac{S_2}{S_1}}{\frac{S_2^2}{S_1^2}\,R_1 + r_2 + R_2}.$$

But E_2, the effective electromotive force in the secondary circuit, is equal to $(r_2 + R_2)\,i_2$; hence it follows that—

$$i^2 = -\frac{E_1\,\frac{S_2}{S_1}}{\frac{S_2^2}{S_1^2}\,R_1 + r_2 + R_2}. \qquad (6)$$

Now if the condition of supply in the mains is such as to give constant-potential at the terminals of the primary circuit, we may take E_1 and R_1 as referring to that which is internal to the primary coil; and it is evident that the effect of the transformer is to reduce the volts in proportion to the ratio of the windings, and to add to the resistance of the secondary circuit a term equal to the resistance of the primary circuit reduced in proportion to the square of the ratio of the windings. It also follows, from the negative sign in (6), that the two currents are in exactly opposite phases.

An important study of the theory of transformers has been made by Prof. Perry,[1] who finds several important results. If it be assumed that there is no magnetic leakage and that there are no magnetic reactions in the outer secondary circuit, then, though the lag of primary current behind the impressed primary voltage varies considerably at different loads, yet the lag of the secondary current behind the impressed primary voltage is always nearly 180°; and, whatever the

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[1] *Philosophical Magazine*, August 1891.

form of the impressed primary curve of volts, the resultant curve of secondary amperes is of the same form. But if there is even a small amount of leakage—as little as 1·33 per cent. of the magnetic flux—these conclusions must be modified, the secondary current being now not nearly exactly in opposite phase to the primary voltage, though almost exactly in opposite phase to the primary current, the lag of which depends *inter alia* on the coefficient of leakage.

Professor Perry has lately further investigated the theory of a transformer wound with any number of separate circuits. Of this investigation, which is otherwise unpublished, the following are the chief points.

Let E_1, E_2, E_3 . . . . &c., be the independent impressed volts in the various circuits. Assume that there is no magnetic leakage. Let the ampere-turns be written

$$A = S_1 i_1 + S_2 i_2 + \ldots . S_x i_x.$$

Let the permeance of the core be written

$$\sigma = \frac{a\mu}{l} 4\pi \div 10,$$

where a is the cross-section and l the length of the core. It is assumed that μ is a constant for a given cycle.

Let the symbol θ stand for the operator $\frac{d}{dt}$. The numerical value of this operator will be in practice a quantity of the order of magnitude 600; for, assuming the alternations n to be about 100 per second, and that the magnetization of the core follows approximately a sine-function of the time, it results that the induced electromotive-forces will be also sine-functions differing $\frac{\pi}{2}$ in phase: for

$$\frac{d(\sin 2\pi n t)}{dt} = 2\pi n \cos 2\pi n t = 2\pi n \left(\sin 2\pi n t - \frac{\pi}{2}\right).$$

Whence $\frac{d}{dt} = 2\pi n$, or is numerically 628.

Then in any circuit the current sent through its resistance will depend only on the impressed volts in that circuit (if any) and the volts due to the inductive action of the core. There is no need to divide the latter arbitrarily into separate parts, a self-inductive part and parts due to mutual inductions with each of the other circuits.

Hence we may at once write :—

$$\begin{aligned} E_1 &= R_1 i_1 + S_1 \sigma \theta A, \\ E_2 &= R_2 i_2 + S_2 \sigma \theta A, \\ E_3 &= \ldots\ldots \\ &\ldots\ldots\ldots \\ E_x &= R_x i_x + S_x \sigma \theta A. \end{aligned}$$

There being as many equations as circuits. Now multiply each equation severally by $\frac{S_1}{R_1}$, $\frac{S_2}{R_2}$, &c. . . . .; and add them together, giving :—

$$\Sigma \frac{S}{R} E = A + q \sigma \theta A,$$

$$\text{where } q = \frac{S_1^2}{R_1} + \frac{S_2^2}{R_2} + \ldots\ldots + \frac{S_x^2}{R_x}.$$

In this quantity q the important term for actual work is the first, because in all the other terms the R part is relatively large, owing to the presence of external resistances, unless any of the circuits is short-circuited. Any closed internal circuit in which eddy-currents might occur may be treated as a term in this series, and might not be negligible in comparison with the first term. Now writing the symbol -1 as the exponent of an inverse operation, we have for the value, at any instant, of the total ampere-turns :—

$$A = (1 + q \sigma \theta)^{-1} \Sigma \frac{S}{R} E.$$

Inserting this in any of the equations, and taking as typical of the lot the pth circuit, we get for the current in the pth circuit,

$$i_p = \frac{E_p}{R_p} - \frac{S_p}{R_p} (1 + q \sigma \theta)^{-1} \sigma \theta \, \Sigma \frac{S}{R} E.$$

We have thus got an expression for the current in any circuit, whatever the electromotive-forces or resistances in any of the circuits.

To apply this to the ordinary case of a transformer having but one primary circuit, we have merely to write E_2, E_3, &c., $= 0$. And for convenience we will consider R_1 as the internal resistance only, so that we may replace E_1 by V the volts at the primary terminals. We still retain the possibility of any number of secondary or induced circuits. We then have:

$$A = \frac{S_1}{R_1}(1 + q\sigma\theta)^{-1}\,V \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$i_1 = \frac{R_1}{V} - \frac{S_1^2}{R_1}\,\frac{\sigma\theta}{1 + q\sigma\theta}\,V \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$i_p = 0 - \frac{S_p\,S_1}{R_p\,R_1}\,\frac{\sigma\theta}{1 + q\sigma\theta}\,V \quad . \quad . \quad . \quad (3)$$

Now since in practice $\theta \gtreqless 600$, $q\sigma\theta$ is large compared with 1. Hence the last results reduce to

$$A = \frac{S_1}{R_1\,q\,\sigma}\int V\,dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

$$i_1 = \frac{V}{R_1} - \frac{S_1^2}{R_1}\,\frac{V}{q} + \frac{1}{q\,R_1\,\sigma}\int V\,dt \quad . \quad . \quad (2a)$$

$$i_p = -\frac{S_p\,S_1}{R_p\,R_1}\,\frac{V}{q} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3a)$$

If there is no load on any of the secondaries, R_2, R_3, &c., are $= \infty$, and $q = S_1^2/R_1$;

$$i_1 = \frac{1}{S_1^2\,\sigma}\int V\,dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2b)$$

or at full load

$$i_1 = \frac{V}{R_1}\left(1 - \frac{S_1^2}{q}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2c)$$

For further discussions on alternating transformers see—

Ferraris: *La Lumière Électrique*, xvi. 399, 1885; xxvii. 518, 1888; and *Electrical Review*, xvi. 256, 343 seqq. 1885; xxii. 221, 252, 1888.

G. Kapp: *Industries*, April 1887; and *Electrician*, 1887. Also *Journal Soc. Teleg. Engineers*, xvii. 96, 1888, with discussion thereon.

G. Forbes: *Journ. Soc. Teleg. Engineers*, xvii. 153, 1888.

Rechniewski: *La Lumière Électrique*, xxv. 613, 1887.

Peukert and Zickler: *Zeitschrift fur Elektrotechnik*, 1886; and *La Lumière Électrique*, xxi. 276, 1886. Also *Electrical Review*, xix. 80, 1886.

CONSTANT-CURRENT ALTERNATING TRANSFORMERS.

Transformers arranged so that the two self-inductions of the two coils are high compared with the mutual induction between them have been designed by Elihu Thomson and by Stanley for the purpose of yielding alternating currents of a constant number of virtual amperes. Swinburne[1] has pointed out that a hedgehog transformer will answer in this way if the primary and secondary coils are wound on opposite ends instead of being wound close together. An ordinary transformer can be adapted to such service if a choking-coil is introduced into the secondary circuit. The use of constant-current apparatus is for feeding arc and glow lamps in series.

USE OF TRANSFORMERS FOR REGULATING ALTERNATORS.

By use of transformers it is possible to attain a means of self-regulation akin to the methods of compound winding adopted for continuous-current dynamos. Assuming that an initial and constant excitation can be afforded by a separate exciter, it remains to supplement this by a variable excitation which, in the case of constant-potential distribution, must be proportional to the main current, or in the case of constant-current distribution must be proportional to the resistance in the circuit. Various combinations have been suggested by Zipernowsky, Kennedy, and Schallenberger.

Fig. 478 shows Zipernowsky's arrangement, and represents diagrammatically a machine with internal revolving field-magnet of eight poles. The armature consists of eight stationary coils, seven of which are joined in series to feed the main circuit, the eighth coil S being separated from the rest and used to provide excitation for the field-magnets, its currents being conveyed in through a suitable commutator on the shaft of the machine. In the main circuit, just beyond the terminals of the machine, is inserted the primary coil of a small transformer T, the secondary of which is connected with the exciting circuit. In this way an additional excitation is procured, always proportional in amount to the currents that are flowing in the main circuit. It is possible to avoid using the coil S by substituting the secondary of another transformer, the primary of which is placed as a shunt across the mains.

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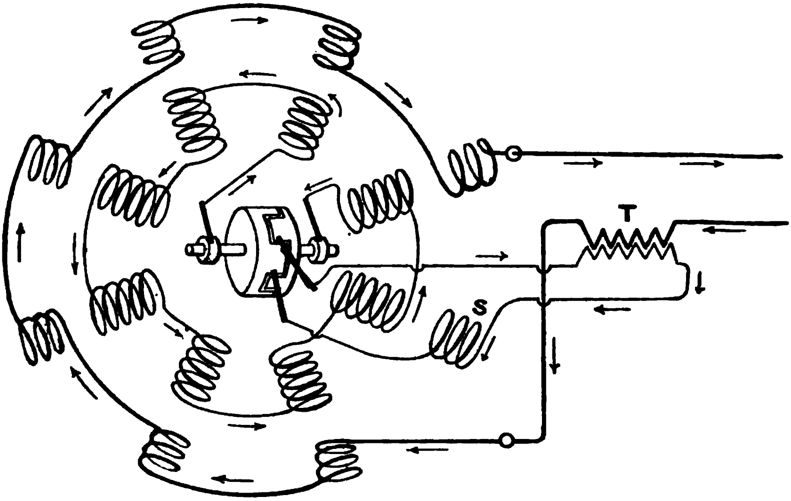
[1] *Journal Inst. Electrical Engineers*, xx. 192, 1891.

FIG. 478.



ZIPERNOWSKY'S METHOD OF COMPOUNDING ALTERNATE-CURRENT DYNAMO.

MOTOR-DYNAMOS.

These are of two sorts: (1) for transforming a continuous current at any voltage to a continuous current of different strength at a different voltage; (2) for transforming a continuous current into an alternating one, or *vice versâ*.

CONTINUOUS-CURRENT TRANSFORMERS.

Gramme, in 1874, constructed a machine with a ring-armature wound with two circuits—one of coarse wire, the other with fine wire, having eight times as many turns. Two separate commutators were connected with the two windings. This machine could be used for transforming either from high to low potential or *vice versâ.* The same end can be less conveniently attained by uniting on one shaft the armatures of two dynamos, one to be used as a motor driving, the other as a generator; and these may have separate field-magnets, or a common field magnet. In England, continuous-current transformers have been introduced with success by Messrs. Laurence, Paris, and Scott,[1] who employ a 2-pole machine with cast-iron frame and an armature wound with double circuits. There is very little sparking with such machines, as the reactions in the two sets of coils tend to correct each other. The field-magnet is excited as a shunt to the low-potential armature coil. Swinburne has discussed many possible combinations, including one for transforming from a constant current to a constant-potential condition of distribution. In the Chelsea central station a number of motor-dynamos are used. They have been described in detail by Major-General Webber,[2] and include several types, some being by Laurence and Scott, others of Elwell-Parker construction.

The following are particulars of an Elwell-Parker continuous-current transformer, closely resembling the machine drawn in Plate VI., drum wound, but having a commutator at each end of the armature.

	Primary.	Secondary.
Volts	1000	110
Amperes	40	360
Resistance of armature winding (ohms)	0·427	0·0052
Conductors around armature ..	648	72
Segments in commutator	162	36

Speed 500 revolutions per minute.
Field-magnets: shunt-wound with 3080 turns; resistance 8·5 ohms.
Armature core: diameter of disks $16\frac{5}{16}$ in.; nett cross section of iron 326 sq. in.
Efficiency of double transformation: at full load 83 per cent.; at half load 75 per cent.

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[1] See *Electrician,* xix. 517, October 1887; and *Electrical Review,* xxii. 4, 1888.

[2] *Journal Inst. Electrical Engineers,* xx. 63 to 69, 1891, giving drawings and data of three machines.

A somewhat different system of continuous-current transformation has been suggested by Cabanellas,[1] and patented by Edison,[2] in which neither armature nor field-magnet revolves, but in which, by means of a revolving commutator, the magnetic polarity of a double-wound armature is continually caused to rotate. In a further modification of this idea, due to Jehl and Rupp, a mass of iron, which completes the magnetic circuit, rotates within the double-wound ring.[3]

It has been proposed to employ a motor-dynamo to compensate the drop in voltage on long mains by inserting into the main at a distant point a series-motor driving an armature placed as a shunt across the mains. Lahmeyer[4] calls this device a "far-leading" dynamo (Fernleitungs-dynamo).

Another combination is useful for three-wire and five-wire systems of distribution, a number of armatures or windings on the same shaft being connected across the various pairs of mains. If at any pair of mains the potential drops, this armature will begin to feed this pair, being driven by the other armatures as motors. Such a device is called an "equalizing" dynamo (Ausgleichungs-dynamo).

For further notices of the methods of continuous-current transformation, the reader is referred to articles by Elihu Thomson, in *Electrical World*, x. 108, 1887; by R. P. Sellon, in *Electrician*, xx. 633, 1888; and by Rechniewski, in *La Lumière Électrique*, xxv. 416, 1887.

THEORY OF CONTINUOUS-CURRENT TRANSFORMERS.

Let $\mathcal{E}$ be the potential at terminals of the primary or motor part, and e that at terminals of the secondary or generator part. Let the i_1, r_1, and C_1 stand respectively for the armature current, armature resistance, and number of armature conductors of the primary part; and i_2, r_2, and C_2 for the corresponding quantities of the secondary part. Then the two induced electromotive-forces will be—

$$E_1 = n\,C_1\,\mathsf{N}, \text{ and } E_2 = n\,C_2\,\mathsf{N}\,; \text{ and}$$
$$E_1 = \mathcal{E} - r_1\,i_1, \text{ and } E_2 = e + r_2\,i_2.$$

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[1] See *La Nature*, p. 43, 1882.

[2] Specification of Patent, 3949 of 1882; and *Electrician*, xix. 479, 1887.

[3] See *Electrician*, xix. 514, 1887; xx. 7, 1887; and Specification of Patent, 2130 of 1887.

[4] *Centralblatt für Elektrotechnik*, xi. 402, 1889.

Now write p for $C_1 \div C_2$ (the reciprocal of the *coefficient of transformation*), and we have—

$$pe = \mathcal{E} - r_1 i_1 - p r_2 i_2.$$

But the electric work done on and by the armature is equal, assuming loss by eddy-currents and hysteresis to be negligible, or $E_1 i_1 = E_2 i_2$; whence $i_2 = p\, i_1$, so that the last equation becomes—

$$e = \frac{\mathcal{E}}{p} - \left(r_2 + \frac{r_1}{p^2}\right) i_2.$$

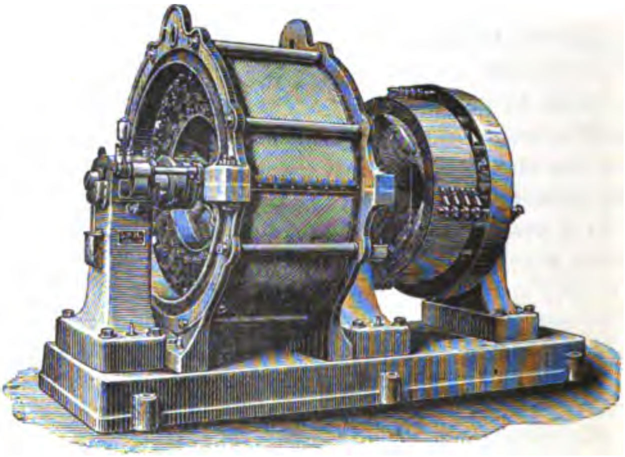
This shows that everything goes on in the secondary circuit as though the potential were reduced from that of the primary mains in proportion to the respective numbers of windings on the armature; and as though there were added to the internal resistance of the secondary circuit a resistance equal to that of the primary winding multiplied by the square of the coefficient of transformation. The ratio of transformation is independent of the speed and of the magnetism, though these two quantities depend inversely on one another. If the dynamo (or secondary) part is compound wound the speed may be very nearly constant at all loads; but there is little advantage in this, as the speed always adjusts itself to what is wanted. If the distant generator supplying the system is properly over-compounded it will keep the voltage at the lamps constant, though the transformer is interposed. The objections to the use as transformers of running machines are almost entirely met by the considerations that these machines run sparklessly (owing to the balancing of the self-inductions of the two windings), and with very little friction at the bearings, because the driving and driven parts are both contained in the one rotating part.

CONTINUOUS-ALTERNATING TRANSFORMERS.

To change an alternating current to a continuous one, or *vice versâ*, there is required a combination of an alternator and a continuous-current machine, to serve one as generator, the other as motor. This may consist of two separate machines coupled together, as shown in Fig. 479, which represents an alternator combined with an internal-pole continuous-current dynamo, both of Siemens' pattern, to transform from 2000 volts alternating to 150 volts continuous, for charging accumulators, &c.

But it is not necessary for this purpose to couple two separate machines. Consider the armature of any ordinary dynamo, say, a 2-pole ring machine. If, in addition to the ordinary commutator, there are provided two, three or four separate contact-rings, united severally to two, three or four points situated symmetrically around the ring,[1] such a machine may be used to give out or receive alternating currents of two, three, or four phases; one winding serving for both kinds of currents. Multipolar machines are preferable for this purpose as giving without undue speed of driving more rapid alternations than 2-pole machines. Such multiplex machines were shown at Frankfort in 1891 by Schuckert, Haselwander, and Dobrowolsky.

FIG. 479.



CONTINUOUS-ALTERNATING TRANSFORMER.

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[1] Such a machine—an "E" Gramme with two contact rings added by Dr. R. M. Walmsley—has been used for some years in the Technical College, Finsbury.

CHAPTER XXVI.

ELECTRIC TRANSMISSION OF ENERGY.

In all problems relating to the electric transmission of power, whether over short or long distances, it is vital to remember that there are two factors to be considered, the *current* and the *pressure* (or potential) at which it is transmitted. In the ordinary distribution of electric energy from central stations in cities, whether with direct or alternating currents, it is usual to observe the condition of *constant pressure*, the current being varied in proportion to the demand. But for series lighting, it is possible to observe the other condition of maintaining a *constant current*, the pressure being varied in proportion to the number of lamps in the circuit. It is well to bear this distinction in mind in the problem of transmission to a distance, although in fact power may be electrically supplied without conforming to either of these prescribed conditions of supply. We have seen, p. 560, how it came to be recognized that the secret of success in long distance transmission lay in the use of high voltages, as this permitted the use of small currents, and therefore of thin conducting wires. We may with advantage recapitulate the problem of economy of transmission.

It is required first to determine the relation between the potential at which the current is supplied to the motor, and the heat-waste in the circuit.

Let ΣR stand for the sum of all the resistances in the circuit; then, by Joule's law, the heat-waste is (in watts) $i^2 \Sigma R$. And since $i = \frac{\mathcal{E} - E}{\Sigma R}$, we may write;

$$\text{heat-waste} = \frac{\mathcal{E} - E)^2}{\Sigma R}.$$

Now suppose that without changing the resistances of the circuit we can increase $\mathcal{E}$, and also increase E, while keeping $\mathcal{E} - E$ the same as before, so that the current will be the same: it is clear that the heat loss will be precisely the same as before. But how about the work done? Let the two new values be respectively $\acute{\mathcal{E}}$ and $\acute{E}$. Then the electric energy expended is

$$\acute{W} = \acute{\mathcal{E}} i,$$

and the useful work done is

$$\acute{w} = \acute{E} i.$$

That is to say, with no greater loss in heating, more energy is transmitted, and more work done. Also the efficiency is greater, for

$$\frac{\acute{w}}{\acute{W}} = \frac{\acute{E}}{\acute{\mathcal{E}}},$$

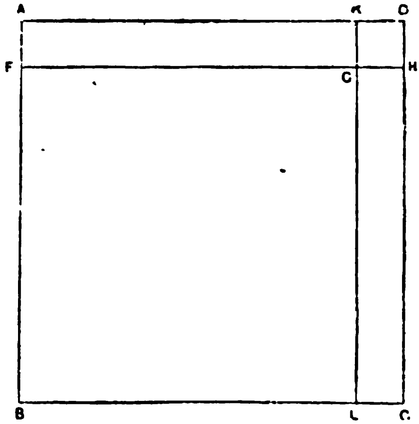
and this ratio is more nearly equal to unity than $\frac{E}{\mathcal{E}}$, because both $\mathcal{E}$ and E have received an increment arithmetically equal. As an example, suppose $\mathcal{E}$ to be 100 volts and E 90 volts, and the sum of the resistances to be 1 ohm. Then i will be 10 amperes. The power supplied will be 1000 watts; that utilized will be 900 watts; the heat-waste is 100 watts; and the electrical efficiency 90 per cent. Now suppose the voltages increased so that $\acute{\mathcal{E}}$ is 1000 volts, and $\acute{E}$ 990 volts. The current will still be 10 amperes. The power supplied will be 10,000 watts, of which 9900 will be utilized and 100 wasted in heat. We have 10 times as much power transmitted, with the same heat-waste as before, and the efficiency has risen to 99 per cent. Clearly, then, it is an economy to work at high voltage. The importance of this matter cannot be overrated. But how shall we obtain this higher electromotive-force? there are four ways open to us. [*i*] The simplest expedient is that of driving both generator and motor at higher speeds. The objections to this expedient are the purely mechanical considerations of liability to heating of bearings and centrifugal flying. [*ii*] A second way is to wind the armatures of both machines with many coils of wire having many turns. This expedient has, however, the effect of putting great resistances into the circuit. This circumstance may, nevertheless, be no great drawback, if there is already a great resistance in the circuit—as, for example, the resistance of many miles of wire through which the power is to be transmitted. In this case, doubling the electromotive-force will not double the resistance. Even in the case where the line resistance is insignificant, an economy is effected by raising the electromotive-force. For, as may be deduced from the equations, when $\mathcal{E} - E$ is kept constant, the effect of doubling the electromotive-force is to increase the efficiency, even when the resistance of the line is very small as compared with that of the machines, and to double it when the resistance of the line is very great as compared with that of the machines. It is, in fact, worth while to put up with the extra resistance, which we cannot avoid if we try to secure high electromotive-force by the use of coils of fine wire of many turns. [*iii*] A third way, not open to any of these objections, is to increase the magnetic field by employing a more powerful field-magnet. [*iv*] A fourth way is to put several machines in series with one another so as to add their separate electromotive-forces.

The advantage derived in the case of the electric transmission of energy from the employment of very high electromotive-forces in the two machines is also deducible from the diagram.

Let Fig. 372, given on p 568, be taken as representing the case where $\mathcal{E}$ is 100 volts and E 80 volts. Now suppose the resistances of the circuit to remain the same while $\mathcal{E}$ is increased to 200 volts and E to 180 volts. (This can be accomplished by increasing the speed or the magnetism of both the generator and the motor to the requisite degrees.) $\mathcal{E} - E$ is still 20 volts, and the current will be the same as before. Fig. 480 represents this state of things. The square K G H D which represents the heat-waste is the same size as before; but the energy spent per second is twice as great, and the useful work done is more than twice as great as previously.

High voltage, therefore, means not only a greater quantity of power transmitted, but a higher efficiency of transmission also. The efficiency of the system in the case of Fig. 372 was 80 per cent.; in the case of Fig. 480 it is 90 (the dynamos used being supposed "perfect"); and whilst double energy is expended, the useful return has risen 2¼ times.

FIG. 480.



In the attempt of M. Marcel Deprez to realize these conditions, in the transmission of power from Miesbach to Munich in 1882, through a double line of telegraph wire, over a distance of 34 miles, high electromotive-forces were actually employed. The machines were two ordinary Gramme dynamos, the magnets being series-wound, similar to one another, but their usual low-resistance coils had been replaced by coils of very many turns of fine wire. The resistance of each machine was 470 ohms, whilst that of the line was 950 ohms.[1] The velocity of the generator was 2100 revolutions per minute; that of the motor, 1400. The difference of potential at the terminals of the generator was 2400 volts; at that of the motor, 1600 volts. According to Professor von Beetz, the President of the Munich Exhibition, where the trial was made, the actual mechanical efficiency was found to be 32 per cent. In Deprez's later experiments, in 1886, between Creil and Paris,[1] the potentials were 6004 and 5456 volts respectively; and according to M. Levy the mechanical efficiency as measured by dynamometers was 44·81 per cent., the distance being about 36 miles. M. Deprez has given the rule that the efficiency $\frac{w}{W}$ is obtained, in the case where two identical machines are employed, by comparing the two velocities at the two stations. Or

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[1] These figures, and those which follow, are given on the authority of the President of the Munich Exhibition, Professor von Beetz.

$$\frac{w}{W} = \frac{n_2}{n_1},$$

Where n_1 is the speed of the generator, n_2 that of the motor. There is, however, the objection to this formula, that the electromotive-forces are not proportional to the speeds, unless the magnetic fields of the two machines are also equally intense, and the current running through each machine the same. This is not the case if there is any leakage along the line. Further, even though the current running through the armatures and field-magnets in the generator which creates the current, and in the motor which utilizes the current, be absolutely identical the intensities of the magnetic fields of the two machines are not equal, even though the machines be absolutely identical in build: the reaction between the armature and field-magnet in the dynamo that is used as a motor is different from that in the dynamo which is being used as the generator.

In an experiment, M. Fontaine,[2] by using several Gramme machines coupled in series at each end of a line, the resistance of which was 100 ohms, succeeded in transmitting 50 horse-power with a mechanical efficiency of 52 per cent. This experiment realized the suggestion made in 1879 by Elihu Thomson for the economic use of several machines in series. Seven machines were used, of similar construction, resembling Fig. 325, and each weighing 1200 kilos., and of about 16 kilowatts capacity. Four were united in series at the generating end, and driven at 1298 revolutions per minute by a steam engine indicating 113 HP. Brake tests at the generating end showed the actual HP. to be 95·88. The other three machines were used as motors, their power being measured by a brake. They gave out 49·98 HP. at 1120 revolutions per minute. The current was 9·34 amperes. The result is that there was a nett efficiency of 52 per cent. The resistance of the machines was about 11½ ohms each. The voltage at the generating end of the line was 5996 volts: that at the receiving end was 5062 volts.

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[1] *Electrician*, xvii. 318, 1886.

[2] *L'Electricien*, x. 707, 1886.

EFFICIENCY OF TRANSMISSION.

It can readily be shown that with two series dynamos, the electrical efficiency of transmission, when there is no leakage, is the ratio of the electromotive-forces developed in the armatures of the two machines. To do this we will consider separately the efficiencies of the three parts of the system. Writing E_1 for the electromotive-force developed in the generator, E_2 for that of the motor, r_1 and r_2 for their respective internal resistances, we shall then have

$$\text{Efficiency of generator} \quad .. \quad \eta_1 = \frac{E_1 i - r_1 i^2}{E_1 i};$$

$$\text{Efficiency of line} \quad .. \quad .. \quad \eta_2 = \frac{E_2 i + r_2 i^2}{E_1 i - r_1 i^2};$$

$$\text{Efficiency of motor} .. \quad .. \quad \eta_3 = \frac{E_2 i}{E_2 i + r_2 i^2}.$$

Hence the resulting efficiency of the whole system will be

$$\eta = \eta_1 \times \eta_2 \times \eta_3 = \frac{E_2}{E_1}.$$

If the machines are shunt-wound or compound-wound, or if there is leakage on the line, the currents through the armatures will no longer be alike in the two machines. Writing the respective armature currents as i_1 and i_2, we shall have in this case, as the electrical efficiency of transmission,

$$\eta = \frac{E_2\, i_2}{E_1\, i_1}.$$

As an example we may refer to experiments[1] made in 1887 with Brown's direct-current dynamos (Plate IX.), between Kriegstetten and Solothurn, through a conductor of 9·23 ohms resistance. In one experiment, the observed values were—E_1 1231·6, E_2 988·6, i_1 14·204, i_2 14·177. The actual horse-power measured at the two ends showed a nett mechanical efficiency of 74·7 per cent. In this case the *nett* efficiency of the generators was 88·8 per cent., that of the motors was 88·1 per cent., whilst the efficiency of the line was 95·4 per cent.

Another example[2] of transmission with direct currents is afforded by the plant at Steyermühle (Tyrol), where two of Brown's 2-pole dynamos with Gramme rings are used to send about 8 HP. to a distance of 600 metres through a double line of copper wire. The following are particulars of the machines. *Generator*, 67 amp. at 1000 volts at terminals, at 575 revs. per min. Turns of wire on armature 504, in 126 sections of 4 turns each. Diam. of core rings, 70 cm. Diam. of magnet cores 40 cm. These are series-wound with 371 turns each. *Motor* only differs in having 456 turns on armature in 114 sections of 4 turns each, and with diam. of magnet-cores 38·1 cm. Brake measurements showed that the generator absorbed 98 HP., whilst the motor gave out 79 HP.; a commercial efficiency of 86 per cent.

A simple problem in the electric transmission of power is the following:—Suppose that one were desirous of working a motor, so as to do work at the rate of a specified number of horse-power, and that the wire available to bring the current cannot safely stand more than a certain current, without being in danger of becoming heated unduly. It might be desirable to know what electromotive-force such a motor ought to be capable of giving back, and what electromotive-force must be applied at the transmitting end of the wire. Let P stand for the number of horse-power to be transmitted, and i or the maximum strength of current that the wire will stand

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[1] See H. F. Weber, in *Schweiz. Bauzeitung*, xi. Nos. 1 and 2, 1888; and *Journ. Soc. Telegr. Engineers*, xvii. 337, 1888.

[2] *Elektrotechnische Zeitschrift*, xi. 11, 1890.

(expressed in amperes). Then by the known rule for the work of a current, since

$$\frac{\mathrm{E}i}{746} = \mathrm{P},$$

$$\mathrm{E} = \frac{746\,\mathrm{P}}{i}$$

gives the condition as to what electromotive-force (in volts) the machine must be capable of giving, when run at the speed it is eventually to run at as a motor. Moreover, the primary electromotive-force, $\mathcal{E}$, must be such that

$$\frac{\mathcal{E} - \mathrm{E}}{\Sigma\,\mathrm{R}} = i,$$

where $\Sigma\,\mathrm{R}$ is the sum of all the resistances in the circuit. Whence

$$\mathcal{E} = \mathrm{E} + i\,\Sigma\,\mathrm{R}.$$

Which gives the required primary electromotive-force.

GRAPHIC METHODS APPLIED TO MOTOR PROBLEMS.

Of the following problems, the first two relate to series motors, and are due to Dr. E. Hopkinson and to Mr. Alexander Siemens.[1]

Given a system of distributing mains supplying electricity at a constant potential, $\mathcal{E}$, *it is required to construct a motor which when working with a given load shall make n revolutions per minute.*

Taking, in Fig. 481, as usual, the currents as abscissæ, and the electromotive-forces as ordinates, draw O M to represent the potential $\mathcal{E}$ of the main in volts. Now, makers of dynamos know from experience what percentage of the electrical energy supplied to a machine of the type they make is absorbed in maintaining the magnetic field. Take a point N in O M such that N M ÷ O M represents this percentage. Also it is known what percentage of the energy thus taken up by the armature, and converted into mechanical work, is wasted in friction at the bearings and brushes. Take the point R such that N R ÷ O N represents the percentage so wasted. From O x cut off O H such that the area O H R′ R represents the actual mechanical output of the motor in watts. For example, if the motor is to realize 1 horse-power, then the area O H R′ R must equal 746 watts. Then O H represents the current (in amperes), and H P is the counter electromotive-force which the motor must exercise. The motor, then, must be such that, running at *n* revolutions per minute, its characteristic will pass through P. The economic coefficient will obviously be equal to H P ÷ H M, and the nett efficiency to H R′ ÷ H M′. The energy spent in magnetization is measured by the area N P M,′ the tangent of the angle P N M′ represents the resistance of the armature, and of the magnets in the case of a series motor.

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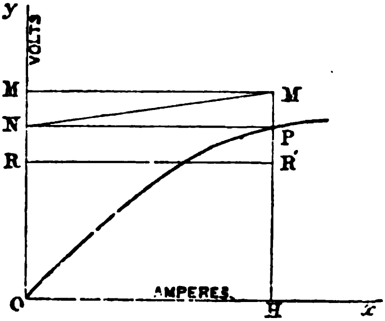
[1] *Journal of the Society of Arts*, April 1883.

FIG. 481.



It is possible to work out similar problems for a shunt-wound motor, and also for the case of a distribution with a constant current.

Given a motor needing a certain current and a certain electromotive-force to enable it to do its work, it is required to construct a suitable generator, the distance between the machines being represented by an electrical resistance of R *ohms.*

Let O P P′ (Fig. 482) be the characteristic of the motor running at its required speed; P H being the volts, and O H the current needed for it. Draw P N horizonally; and draw N M′ from N at an angle such that its tangent represents the sum of the resistances of the motor and line. Then M′ H represents the difference of potential between the terminals of the generator. Then produce H M′ to Q so that H M′ ÷ H Q shall represent the economic coefficient of the machine of the type that is to be used as generator. Then the proper generator will be that which when running at the proper speed will have a characteristic running through O and Q; and the tangent of the angle M' M Q represents the resistance of the armature and field-magnet of the generator.

Another graphic method of comparing the power and efficiency of a motor has been proposed by Mr. Gisbert Kapp. The speeds being taken as abscissæ, the electric horse-power absorbed is plotted out vertically, the number of watts divided by 746 being taken for

FIG. 482.

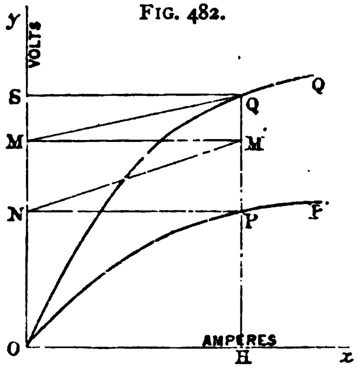
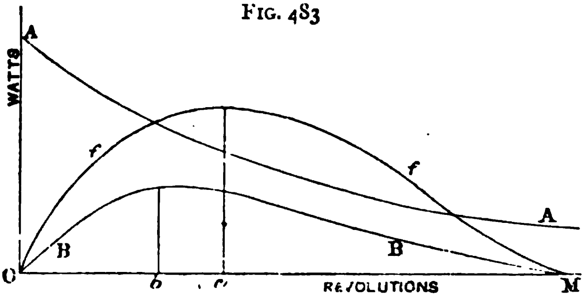


FIG. 483



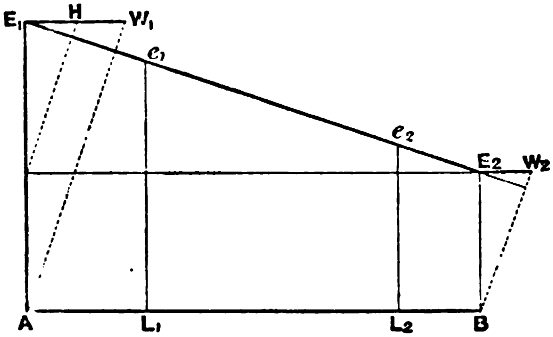
the ordinates. Fig. 483 shows the result in the curve A A, the shape of which will vary with the type, a series-wound motor in this case. A second curve B B is then plotted, the ordinates in this case being the mechanical horse-power observed at different speeds. In both cases the variation of speed is obtained by loading a brake dynamometer with various loads. With a great load the speed is small, the applied electromotive-force very great. With no load, a certain maximum speed O M is obtained at which (owing to the counter electromotive-force developed) very little current passes. Between these two extremes there will be a point *b*, corresponding to a certain speed O *b*, for which the activity is a maximum. Next divide the values of the mechanical work B, by those of the electrical energy spent E at the corresponding speed. These quotients will of course be the commercial efficiency at different speeds. These values are plotted out to an arbitrary scale in the curve *f f*, which shows that the maximum efficiency is attained at the speed corresponding to the point *c*.

GRAPHIC REPRESENTATION OF TRANSMISSION.

A convenient mode of representing graphically the relative amounts of energy expended at the transmitting end and utilized at the receiving end is the following, which is due to von Hefner Alteneck :—

Let (Fig. 484) the perpendicular lines A E_1 and B E_2 represent respectively the electromotive-forces at the transmitting and receiving machines; and let the horizontal lengths A L_1, L_1 L_2, and L_2 B represent respectively the resistances of the machine at A, the line (including return wire), and of the machine at B. Join E_1 E_2: the tangent of slope of this line will represent the current flowing. From A and from B drop perpendiculars upon this sloping line, and produce them to the points W_1 and W_2, level with E_1 and E_2. The lengths of the lines E_1 W_1 and E_2 W_2 will represent relatively the energy transmitted and received. For, by the construction each is proportional to the respective electromotive-force and to the slope of E_1 E_2. The energy lost in heat may, on the same scale, be represented by the length of the line E_1 H.

FIG. 484.



For a further geometrical discussion of the problem of electric transmission of power, see a paper by Reignier, in *La Lumière Électrique*, xxiii. 352, 1887.

ECONOMY OF TRANSMISSION.

As already shown, the economy of transmission depends on the voltage at which the power is transmitted, and on the resistance of the line. The question then arises at what amount ought the latter to be fixed to make the economy a maximum. If one saves heat-waste by putting up a thick copper wire for the line, the interest on the prime cost of the line may more than balance the saving in power. An answer was given in 1881, by Sir William Thomson, to one form of the problem, in which it is assumed (1) that the voltage is fixed, (2) that the power to be transmitted is a fixed amount. If these are the conditions, then the total annual cost of the power wasted in the resistance of the line and of the interest on the copper (including insulation and erection) will be a minimum when these two annual items of cost are equal to one another. Much confusion has arisen from the ignorant application of Thomson's law to other cases than those for which it is true. In 1886, Professors Ayrton and Perry[1] considered some other cases, and have arrived at several important conclusions. If a given amount of power has to be furnished by a motor at one end of a line, using a given voltage at the generator at the other end, maximum economy is obtained, not by keeping the current-density constant, but by making it less, as the length of line to be used is greater. The smaller the voltage that may be employed at the generator, the smaller must the current-density in the line be to obtain the maximum efficiency. More recently, Mr. Kapp,[2] in his Cantor Lectures, has given a more general solution, taking into account the voltage and the cost of the machines as well as that of the line. It is assumed that the annual value of power at the generating station is known, as well as the cost of plant per horse-power. Of the data required to be known, such as primary horse-power, total efficiency, voltage at motor, annual cost of power delivered, and working current, the last mentioned is the most important to be calculated, for from it the other matters can then be found. The following is then Kapp's argument:—

MOST ECONOMICAL CURRENT FOR ELECTRIC POWER TRANSMISSION.

D .. .. Distance in miles.
a .. .. Section of conductor in square inches.
E .. .. Terminal volts at generator.

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[1] *Journal Soc. Telegr. Engineers*, xv. 120, 1886.
[2] *Journal Soc. Arts*, xxxix., July 10, 1891.

e .. .. Terminal volts at motor.
HP_g .. .. .. Actual horse-power required to drive generator.
HP_m .. .. .. Actual horse-power obtained from motor.
i .. .. Current in amperes.
Efficiency of generator 90 per cent.; efficiency of motor 90 per cent.
g .. .. Cost in £ per electrical horse-power output of generator.
m .. .. Cost in £ per actual horse-power output of motor including regulating gear.
$G = {\cdot}9 g\, HP_g$ .. Cost in £ of generator.
$M = m\, HP_m$ .. Cost in £ of motor and regulating gear.
$t = 18{\cdot}2\, D a$ .. Weight in tons of copper in line.
K .. .. Cost in £ per ton of copper, including labour in erection.
s .. .. Cost in £ of supports of line per mile run.
p .. .. Cost in £ of one annual actual horse-power absorbed by generator.
q .. .. Percentage for interest and depreciation on the whole plant.

$$\text{Capital outlay} = g\frac{Ec}{746} + m\,HP_m + Ds + \frac{1{\cdot}6\,KD^2c^2}{Ec - 830\,HP_m} = A.$$

$$\text{Annual cost per brake horse-power delivered} = q\frac{A}{HP_m} + p\frac{HP_g}{HP_m}.$$

$$\text{Put } B = \frac{Ep}{670} + q\frac{Eg}{746}.$$

$\gamma = \frac{830}{E}HP_m$, the current which would be required if the line had no resistance,

and $\beta = \gamma^2\frac{EB}{1{\cdot}6\,qKD^2 + EB}$; then the most economical current at the given voltage E is

$$i = \gamma\left\{1 + \sqrt{1 - \frac{\beta}{\gamma^2}}\right\}$$

$$i = \gamma\left\{1 + \sqrt{\frac{1{\cdot}6\,qKD^2}{1{\cdot}6\,qKD^2 + BE}}\right\}$$

For very long distances the term under the square root approaches unity and the most economical current the value 2γ; from which it follows that under no circumstances will it be economical to lose more than half the total power in the line.

A useful set of tables, showing the cost of laying one additional ton of copper, meaning thereby that part of the capital outlay which is proportional to current, was given by Prof. G. Forbes in his Cantor Lectures[1] of 1885 on the Distribution of Electricity.

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[1] *Journal Soc. Arts*, 1885.

The secret of economy in all long-distance transmission lies, as we have seen, in the use of high voltage. But it is found in practice that continuous-current machines cannot advantageously be used at such high voltages as 3000 and 4000 volts, inasmuch as the commutators will not stand the strain on their insulation. Even putting several machines in series, though it lessens the voltage on each dynamo, does not prevent the risk of break-down of insulation. Hence the superiority of alternate-current apparatus, which requires no commutator. Moreover, where voltages exceeding 10,000 volts are desired, it is found preferable to use low-voltage alternators and motors, and to insert step-up transformers at the generating end, and step-down transformers at the receiving end (as proposed in 1881 by Deprez and Carpentier), since it is much easier to insulate thoroughly the stationary windings of a transformer than the parts of any running machinery. The question whether of alternating systems the ordinary two-phase, or one of the more novel three- or four-phase systems, is to be preferred in long-distance transmission is still an undecided matter.

As an example of transmission to a moderate distance by continuous currents, we may cite the plant at Schaffhausen, erected by the Oerlikon Works of Zürich, where 500 actual horse-power are delivered to the spinning mills electrically, with a nett efficiency of 78 per cent., from turbines in the river 750 yards away, two generators (six-pole over-compounded dynamos designed by C. E. L. Brown) being used, to give each 330 amperes at 624 volts. The motors, which are of the same type, are constructed with field-magnets, which are relatively more powerful than those of the generators, and run without varying more than 3 per cent. in speed between no load and full load. The commutators are guaranteed to last for 20,000 hours.

As an example of long-distance transmission at an extra-high voltage may be cited the experimental line erected in the summer of 1891, from Lauffen to Frankfort, a distance of 175 kilometres. At Lauffen a special low-pressure turbine was fixed in the river Neckar to drive the three-phase alternator, by Brown, described on p. 688, capable of giving (at full power) three alternating currents of about 1400 amperes each at 50 volts. These currents were converted by special transformers into three smaller currents at either 12,500 or 25,000 volts. Three copper wires, each 4 millimetres in diameter, were carried to Frankfort on tall poles; about 10,000 porcelain insulators being, employed, with oil-cups for high insulation. At Frankfort the currents were received into step-down transformers and reconverted to the low-pressure of about 60 volts, to supply either lamps or three-phase motors. Tests[1] were made by a jury, having Prof. H. F. Weber as its head.

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[1] Whilst these sheets are going through the press, unofficial information comes to hand about the yet unpublished tests. It appears that when the high-pressure of 30,000 volts was used the watts supplied at Lauffen were 80,500, and the watts actually received and used at Frankfort were 58,000; showing the gratifying result of an efficiency of 72⅙ per cent.

CHAPTER XXVII.

REGULATORS FOR DYNAMOS.

MEANS of governing the performance of dynamos are needed, not only for keeping the pressure at some constant number of volts or for keeping current at some constant number of amperes, but also for such purposes as to enable the voltage of any one dynamo to be raised in order that it may feed into some distant point of a distributing network.

The output of a dynamo depends on three intrinsic matters, namely, (*i*) speed n, (*ii*) number of armature conductors C, and (*iii*) magnetic flux N; and on two extrinsic matters, namely (*iv*) resistance of the circuit and (*v*) counter electromotive-forces in the circuit. It is therefore clear that any one of these five matters might afford a method of controlling the performance of the machine.

To introduce resistances into the main circuit is always wasteful, and may be dismissed as an uneconomical method of regulation suitable only for experimental purposes. To introduce counter electromotive-forces into the external circuit is usually impracticable. It remains therefore to consider the three intrinsic methods.

Speed governing is clearly limited to those cases where there is a separate engine for each dynamo; and in such cases a special governor will be required instead of the usual centrifugal engine governor.

To alter the number of conductors in a rotating armature whilst it is running is absurd. Their *effective* number can, however, be altered by the device of shifting forward the brushes so that they collect the current not at the point of highest potential, but at some other point. This method virtually uses some of the armature windings, namely, those between the neutral point and the point to which the collecting brush is advanced, to produce internal counter electromotive-forces.

To alter the magnetic flux is the almost universal mode of control; and it may be accomplished in two entirely distinct kinds of way. Since the flux depends on the excitation (or ampere-turns) and on the reluctance of the magnetic circuit, it can be varied by varying either the former or the latter. The excitation may be altered in various ways, (*a*) by hand with the aid of rheostats and commutators in the exciting circuit, or (*b*) automatically by special governors in substitution for the hand, or (*c*) by devices of compound winding. The magnetic circuit may be varied in several ways, as (*d*) by moving the pole-pieces nearer to or further from the armature, (*e*) by opening or closing some other gap in the magnetic circuit, (*f*) by drawing the armature end-ways from between the pole-pieces, (*g*) by shunting some of the magnetic lines away from the armature by applying a magnetic shunt across the limbs. All these magnetic devices have been tried,[1] but not with much success except in small machines.

Hand-regulators.—These consist of sets of sliding contacts to enable the operator to perform one of the following operations:—(1) insert or remove resistance from the exciting circuit of a shunt dynamo (see Edison's Regulator, Fig. 180, p. 279); (2) insert or remove resistances, shunting the magnetizing coils of a series dynamo; (3) cut out more or fewer exciting coils, these being grouped in sections.

CONSTANT PRESSURE AND CONSTANT CURRENT REGULATORS.

In all automatic regulators there is a part which has to act as the brain of the instrument, watching as it were against any variation, and setting into action the mechanism which is to counteract the variation. This watching device is usually some sort of an electromagnet, often a coil with a movable plunger. When the volts are to be kept constant the coil of the controlling device must be wound as a voltmeter coil, that is of fine wire, of high resistance, and connected as a shunt. When the amperes are to be kept constant the controlling coil must be wound like an amperemeter with thick wire, of low resistance, and inserted in the main circuit. Alternators are usually regulated by operating on the circuit of their exciters, the current in the governor coil being derived from the mains by a small transformer.

Goolden's Automatic Regulator.—Automatic regulators are of two species: in one the work of moving the regulator is accomplished mechanically, the control only being electrical; in the other both

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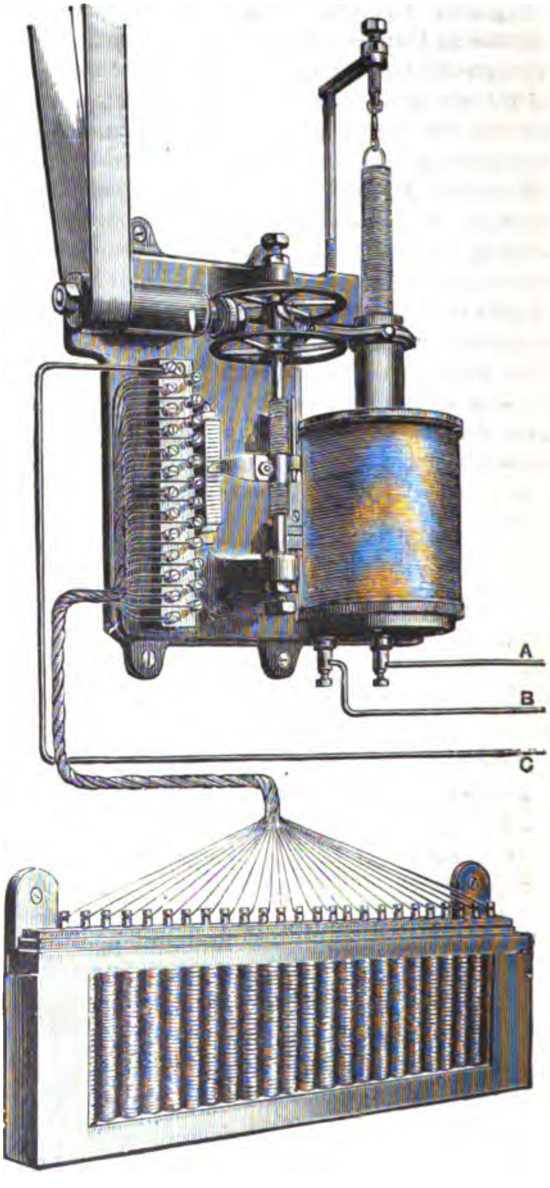
[1] For an example of (*d*) see Firth's method (see *Industries*, ix. 161), in which the polar masses are drawn backwards by screws; and of (*g*) a magnetic shunt applied by Desroziers, *La Lumière Électrique*, xxiv. 394. Other magnetic methods have been used by Goolden and Trotter, Langley, P. Müller, Lontin, and Diehl.

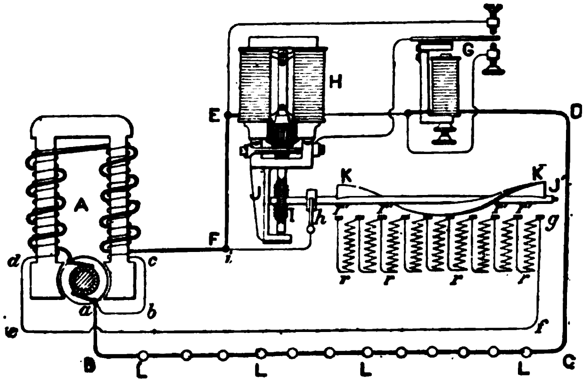
FIG. 485.



GOOLDEN'S AUTOMATIC REGULATOR.

the control and the moving power are obtained electrically. Goolden's regulator, Fig. 485, belongs to the former of these classes. In this instrument there is a row of sliding contacts which are respectively connected to the wires of a resistance-frame or rheostat[1] shown in the lower part of the cut. The sliding piece is worked by a vertical screw, and this is caused to rotate right or left-handedly as may be required under the operation of a double crown-wheel on a sleeve on the vertical spindle, placed between two screws that are kept in rotation by a small pulley driven slowly from the engine. The controlling part—the brain of the apparatus—is the hollow coil of wire on the right, with its suspended iron plunger. When the current in this coil is of proper normal strength the plunger is drawn in just so far that the crown-wheel is not in gear either with the upper or the lower driving screw. If the current in the coil grows weak the plunger rises, causing the crown-wheel to engage in the upper screw, which immediately begins to turn it, so moving the sliding-contact in such a way as to increase the excitation of the dynamo, and bring back the current in the coil to its normal strength. The wires A and B from the governing coil go to the circuit that is to be kept to standard condition, whilst the exciting circuit of the dynamo is connected to C and to the sliding piece.

FIG. 486



MAQUAIRE'S REGULATOR.

Maquairé's Regulator is an example of the second kind, both the controlling and the moving mechanisms being electrical. The governor G consists of an electromagnet, the armature of which is attached to a spring, and when the current through it—in the main circuit of a set of lamps, L L in Fig. 486—is normal, is so balanced that the tongue attached to it lies free between two contact-screws. The dynamo A has two exciting coils. One in the main or lamp circuit: the other is a shunt circuit *a b c d e f g h i*, in which are included the coils *r r* of a rheostat. The contacts of this rheostat are operated by turning a shaft J J, having a tortuous contact-piece K K upon it. The mechanism which turns the shaft J J is a small electric motor, the field-magnets of which H are in the main circuit. By a device explained on p. 593, the armature of this motor can be made to turn in either direction by being made a shunt to either half of the field-magnet of the motor; one brush being connected to the magnetizing coils mid-way between the two limbs, the other being connected to the tongue of the governor G. Hence if the main current becomes too weak the tongue rises, and making contact, causes the motor armature to turn so as to alter the resistance and increase the excitation of the dynamo.

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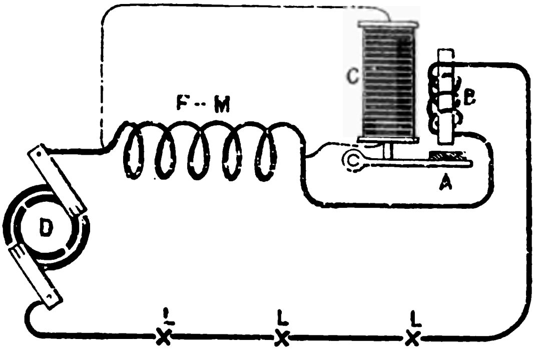
[1] On the construction of such rheostats, choice of wires, and the like, see Herrick, *Electrical World*, xv. 240, 1890; also Ayrton and Mather, *Phys. Society*, 1891.

Brush's Automatic Regulator.—This is a simpler example of a purely electric regulator. A series dynamo is made to yield a constant current by introducing across the field-magnets a shunt of variable resistance, the resistance of the shunt being adjusted automatically by a governing electromagnet whose coils form part of the main circuit. The system is shown in the accompanying diagram

FIG. 487.



BRUSH'S AUTOMATIC REGULATOR.

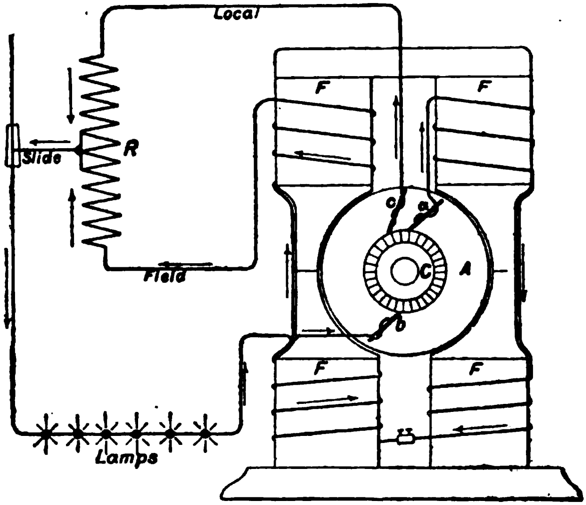
(Fig. 487). The dynamo at D pours its current into the circuit, leaving the commutator (as drawn) by the upper brush, whence it flows through the field-magnets F M, and round the circuit of lamps L L, back to the negative terminal. Suppose now some of the lamps to be extinguished by switches which short-circuit them; the resistance of the circuit being thus diminished there will be at once a tendency for the current to increase above its normal value unless the electromotive-force of the dynamo is at once correspondingly reduced. This is done by the solenoid B in the circuit. When traversed by the normal current it attacts its armature A with a certain force just sufficient to keep it in its neutral position. If the current increases, the armature is drawn upward and causes a lever to compress a column of hard carbon plates C, which is connected as a shunt to the field-magnets. These plates when pressed together conduct well, but when the pressure is diminished their imperfect contact partially interrupts the shunt-circuit and increases its resistance. When A rises and compresses C, the current is diverted to a greater or lesser extent from the field-magnets which are thus under control. This regulator will keep the current constant even though the speed of driving may be irregular.

Thomson-Houston Regulator.—This was described on p. 471, and operates by shifting the brushes so as to bring counter electromotive-forces into play, and is purely electrical.

Statter's Regulator.—This was described on p. 478, and shifts the brushes by a motion derived mechanically from the rotation of the dynamo, but electrically controlled.

Waterhouse's Third Brush Regulator.—In this case the exciting circuit on the dynamo receives and carries a variable part of a current supplying arc lamps in series as in Fig. 488, the other part being carried by a local circuit which, starting from a third brush, joins the lamp circuit at a certain point along a resistance in the circuit. In Fig. 488 the positive brush is marked *a*, and leads through the exciting coils to the resistance R, and there is joined by the local branch from the third brush *c*. The action depends on the armature reaction altering the point of highest potential at the commutator. If, on cutting out one or more lamps, the current in the armature were to increase, the position of maximum potential would be shifted from *a* towards *c*, causing more current to flow by the local branch, and less by the exciting branch, so bringing down the excitation. A special study of this method of regulation has been made by Caldwell,[1] who has shown that it can also be applied to constant pressure regulation.

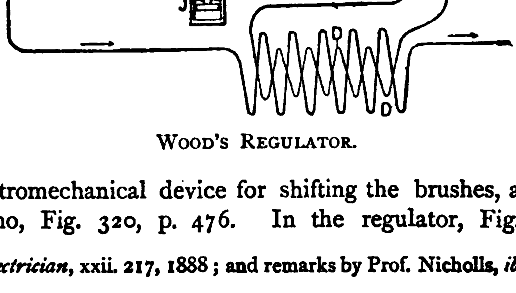
FIG. 488.



WATERHOUSE'S THIRD-BRUSH REGULATOR.

Wood's Regulator.—In this method also a pilot brush is employed, but there are two exciting circuits wound differentially, and there is an electromechanical device for shifting the brushes, attached to the dynamo, Fig. 320, p. 476. In the regulator, Fig. 489, the

FIG. 489.



WOOD'S REGULATOR.

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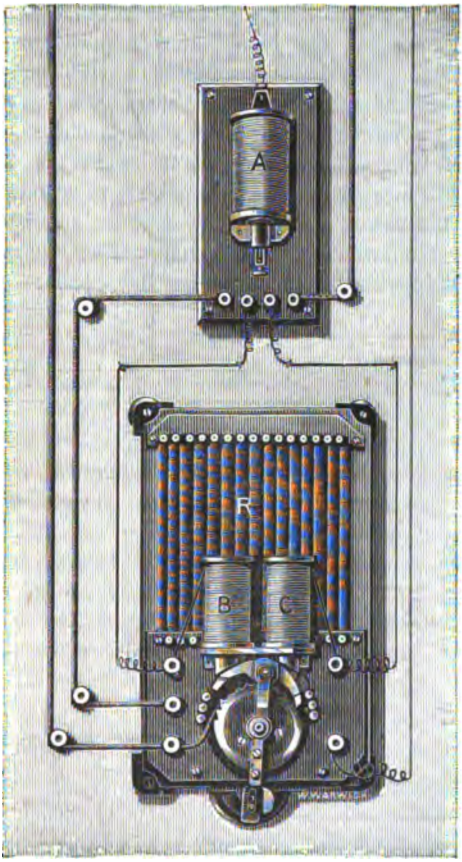
[1] *The Electrician*, xxii. 217, 1888; and remarks by Prof. Nicholls, *ib.*, 441, 1889.

governor coil N actuates a core, the motion of which opens or closes a by-pass circuit of an electromagnet M, which moves the rocker to which the two brushes are attached. When all the lamps are in circuit and the dynamo fully excited, the pilot-brush C is close to B, so that almost no current flows around the demagnetizing circuit *a a*. If now some lamps are cut out, momentarily increasing the current above normal value, the governor core rises and breaks contact at *e f*, causing M to shift the pilot-brush C forward, so that the demagnetizing current is strengthened, so

FIG. 490.



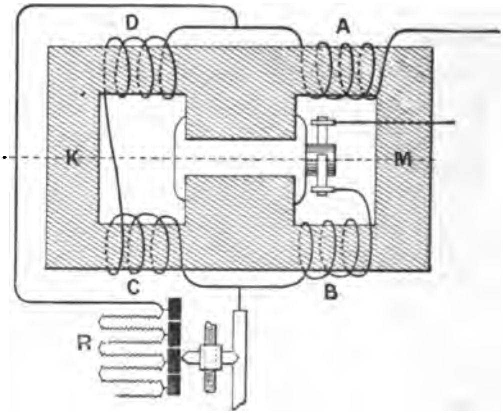
HENRION'S REGULATOR.

reducing the excitation. Sparking at *e f* is minimised by the resistance *r*.

Henrion's Regulator.—Another electromechanical regulator is shown in Fig. 490. The plunger of the governor A, on moving up or down from normal position, works the mechanism by short circuiting one or other of two electromagnets B and C, both of which are also in the main circuit. Below them is an oscillating lever pivoted on a pin carrying two ratchet wheels; and lever carries a double-ended iron pawl. If either magnet is cut out by the governor, the pawl drops over and at once begins to take up teeth on one of the ratchet wheels, thereby moving a contact arm over studs that communicate with the wires of a rheostat.

Ravenshaw and Trotter's Regulator.—This is an interesting example of the use of a magnetic shunt to produce a constant current. In the arrangement in question the number of magnetic lines through the armature core is reduced to any desired degree, without producing instability, while the field-magnet is saturated to its usual degree, by diverting the magnetic lines out of their usual path, into a path of lower magnetic reluctance. The plan of employing a movable keeper of iron was superseded by Trotter's suggestion to fix the keeper and to vary its effect by surrounding it with a counter-magnetizing coil. The double-circuit type of field-magnet is suited for this purpose, one half of the machine being kept saturated as a field-magnet of constant power, whilst the

FIG. 491.



RAVENSHAW AND TROTTER'S MAGNETIC SHUNT.

other half acts a keeper. In Fig. 491 the acting field-magnet is the right-hand half M, with the magnetizing coils A and B; the keeper is the left-hand half K, with the coils C and D. These four coils are connected up in the usual way to give consequent poles at the pole-pieces, but there is a regulating set of resistance R arranged as a shunt to the coils C and D. When the resistance R is small, the coils C and D scarcely receive any current, and consequently nearly the whole of the magnetic lines generated in the magnet pass round the keeper instead of through the armature. By introducing resistance at R the coils C and D begin to excite a counter magnetism and drive back some of the lines out of the keeper and into the armature. The resistances at R are arranged in a graduated set provided with contact pieces, with which contact is made by a slider worked by a governor, such as Fig. 485. It was found necessary[1] to cut a gap in the magnetic circuit of the keeper to prevent sluggishness in the descending magnetizations.

Sperry's Regulator.—This has a mechanical movement for shifting the brushes, operated from the shaft of the dynamo, but electrically controlled. It is shown in Fig. 318, p. 475.

M. Reignier[2] has drawn attention to a solution of the problem of exact governing to procure a constant current by automatically varying the number of coils through which the current is permitted to pass.

ELECTRIC GOVERNORS FOR STEAM-ENGINES.

No centrifugal governor attached to the steam-engine can keep the speed of the dynamo truly constant; for it does not act until the speed has become either a little greater or a little less than the normal value. Few mechanical governors will keep the speed within 5 per cent. of its proper value, under sudden changes of load. Hence the suggestion which underlies all electrical governors, that the admission of steam from the boiler to the engine should be controlled by the electric current itself, the speed of driving being varied according to the demands of the circuit. It is emphatically needed wherever the loads are liable to sudden variations, as in the case of generators for electric railways. Numerous suggestions of a more or less practical nature have been made by Lane-Fox, Andrews, Richardson, and others.

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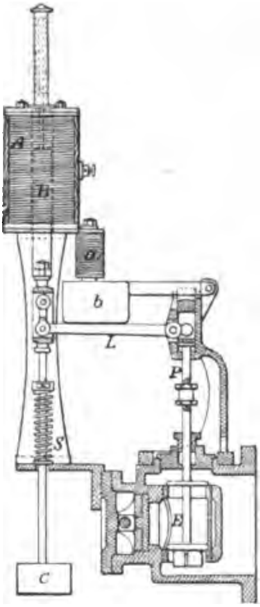
[1] See paper by A. P. Trotter, in *Electrician*, xix. 374, 1887. A drawing of the governor itself is given in the *Electrical Review*, xix. 289, Sept. 17, 1886.

[2] *La Lumière Électrique*, xxvi. 420, 1887.

Richardson's Governor.[1]—This governor is used to maintain either a constant current or a constant potential. In the former case its coils are included in the main circuit and are of thick wire: in the latter they are arranged as a shunt to the mains and are of fine wire. The arrangements are shown in Fig. 492.

FIG. 492.



RICHARDSON'S ELECTRIC GOVERNOR.

The valve which admits steam to the engine is a double-beat equilibrium valve E; its stalk passes upwards and is acted upon by a plunger P, which is pressed down by the shorter end of a lever L, which is in turn connected with a long vertical spindle having a weight C at its lower end, and at its upper end carrying the iron core B, surrounded by the solenoid A. A spring S counterpoises the slight upward pressure of the steam on the valve. When the current passes through the solenoid A, it lifts the core B to a certain height and admits to the engine a sufficient quantity of steam to drive the engine at the speed requisite to maintain the current. Should the resistance of the circuit be increased by the introduction of additional lamps, the core B will fall a little, thereby turning on more steam, until the speed has risen to that now necessary. For additional safety a separate electromagnet *a* is added, which, when in action, holds up the heavy iron block *b*. Should the circuit from any cause be broken, the block *b* instantly descends and cuts off the steam. In some experiments made at Lincoln in 1883, in the author's presence, on a Brush 16-light machine fitted with a Richardson's governor, the following results were attained:—Seventeen arc lamps being alight, six were suddenly switched off: in four seconds the speed of the engine came down from 138 to 107, and the current which was 10·2 amperes had returned to exactly the same value. Seventeen lamps being again alight, the whole were short-circuited, leaving the current running only through the governor and the field-magnets of the dynamo. The engine pulled up in less than one stroke, and in fourteen

[1] See Specification of Patent, No. 288 of 1881.

seconds the speed had come down to 24, the engine just crawling round at a speed sufficient to keep the magnets charged. In another experiment the circuit of the whole seventeen lamps was suddenly broken, the engine running at 140. In fifty-five seconds it had stopped, the steam having been cut off in less than a quarter of a second. No centrifugal governor could have so instantaneously shut off steam: it would not have acted until the engine began to race. With the electric governor the steam was cut off before racing could even begin. At all speeds from 25 up to 146 revolutions per minute, and with any number of lamps from none to seventeen alight, the current was practically kept at a constant value in a most efficient manner. Another of these governors connected with an incandescent-light system working at 92 volts was found to keep the potential correctly to within 1 per cent., even though the number of lamps was varied from 91 to 31, and the boiler-pressure from 32 to 55 lbs. per square inch. It also maintained an absolutely constant potential when but one lamp was alight, though the boiler-pressure was purposely varied from 31 to 55 lbs. per square inch.

Willans' Governor.[1] — This instrument has been applied with great success at Victoria Station and elsewhere. In common with Richardson's governor, it employs the attraction exerted by a solenoid on an iron core to actuate an equilibrium valve; but the action is indirect, the solenoid core operating on the small valve which controls a hydraulic piston, the latter in turn controlling the large steam valve. The arrangement is shown in Fig. 493, where T is the large piston throttle-valve. The throttle-valve spindle passes downwards and is connected direct to the piston of the hydraulic relay. The solenoid A attracts its core B suspended on a spring. The position of B determines that of the lever X, which is connected at one point to the spindle of the throttle-valve and at another to that of the small controlling valve. If the potential at the mains falls, less current flows round A, in consequence B rises, and its projecting ear-piece raises the lever X, admitting more water above the controlling piston, which consequently sinks, drawing down the throttle-valve with great power and admitting more steam to the driving engine. A comparatively small solenoid, actuated by but 0·3 ampere of current and absorbing only about 32 watts of power, may thus bring a force of many pounds to bear upon the steam valve, and will control with ease a 60 horse-power engine.

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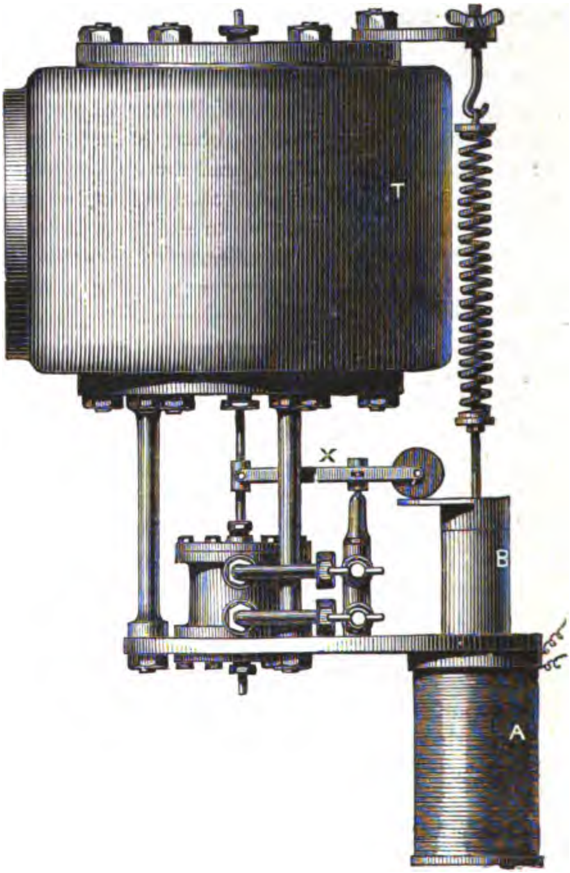
[1] See Specifications of Patent Nos. 1184, 5291, and 5945 of 1883; also paper by P. W. Willans in *Proc. Inst. Civil Engineers*, lxxxi. pt. iii. 1884–5.

FIG. 493.



WILLANS' GOVERNOR.

Jamieson's Governor.—This consists of a copper disk revolving between the poles of a small electromagnet in the circuit, and actuating a throttle-valve by means of a spring and a cone gearing. It was figured in the earlier editions of this work.

One great advantage of the electric governor is that it cuts down the consumption of steam to the actual demands made upon the electric circuit, and prevents injury both to the dynamo and to the steam-engine.

Dynamometric Governing. — Another method of governing dynamos is too important to be omitted. The power transmitted along the shaft is the product of two factors, speed and torque. If ω stands for the angular velocity and T for the torque, then

$$\omega\,T = \text{mechanical power in the armature.}$$

But the activity, or work per second, or power, of a dynamo can be measured electrically, by the product of its electromotive-force into the current it drives through the circuit. If E stands for the electromotive-force, and i for the current, then

$$E\,i = \text{electric power (gross) in the armature.}$$

In a good dynamo the electric power, though not equal to the mechanical power, will exceed 95 per cent. of it. Now we know that, other things being equal, the electromotive-force E of a dynamo is proportional to speed of driving. It follows at once that *the torque will be proportional to the current i.* This at once suggests that a dynamo may be driven so as to give a constant current, provided it be driven from a steam-engine governed *not by a centrifugal governor to maintain a constant speed*, but *by a dynamometric governor to maintain a constant torque or turning moment.* Some good transmission dynamometer, such as that of Morin, or one of the later varieties, such as those designed by Ayrton and Perry, or best of all that designed by the Rev. F. J. Smith,[1] may be adapted to work an equilibrium valve, and would fulfil the above condition of governing.

Prof. E. Thomson has suggested the use of a dynamometric apparatus to govern a constant-current dynamo by the method of shifting the brushes. A description of this governor was given in the second edition of this work.

Governing by Steam-Pressure. — It was remarked above that electric power and mechanical power are each a product of two factors. But in an ordinary steam-engine the work per second also consists of two factors, viz., speed of piston and steam-pressure; and the angular velocity of the shaft is proportional to the former, and its transmitted torque to the latter. Therefore the condition of maintaining a constant current ought to be fulfilled if the pressure is always constant. If the valves are such as to admit a fixed quantity of steam at each stroke, and if the boiler pressure is really kept up, then the average pressure behind the piston ought to be constant. In practice this is never attained on account of the friction of the steam against the steam-pipes and port-holes of the valves. The internal friction in the engine plays the same part in preventing absolutely true self-regulation, as does the internal electrical resistance in the dynamo. An approximation is all that is possible.[1] In an experiment made by M. Pollard with a Gramme dynamo, the current gave deflections on a galvanometer, varying only from 59° to 54°, while additional resistances were introduced into the circuit, which caused the speed to run up from 436 to 726 revolutions per minute. Theoretically, therefore, a constant current ought to be one of the easiest things to maintain with a series dynamo. Have adequate boilers, keep the steam-pressure always at one point, abandon all governors, and admit equal quantities of steam at each stroke whatever the speed; the result *ought* to be a constant current. The condition of maintaining a constant potential cannot be similarly solved, except by employing a shunt dynamo under conditions that are both uneconomical and impracticable. But in the case of constant-current work it is possible to go further toward realizing such results. The existing method of maintaining a constant steam-pressure is to put upon the boiler a pressure-gauge which indicates to the stoker when he is to add more fuel and when to damp down the fire. Let the pressure-gauge be abandoned, and instead, let there be provided at the side of the furnace an amperemeter, and let the stoker feed or damp his furnace fires according to the requirements of the electric system of distribution. Is there any valid reason why such a method of government should not be efficient in practice, at least in the case of the series dynamo for constant currents?

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[1] See his excellent little book on *Work-measuring Machines*, published by Messrs. E. and F. N. Spon.

Finally, to render the system truly automatic, it is conceivable that mechanical stoking appliances might be arranged, under the control of the amperemeter or voltmeter, to supply the fuel in proportion to the number of lamps alight.

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[1] See Edmunds in *Journal Soc. Telegr. Engineers*, xvii. 697, 1888; also *The Electrician*, xxii. 349, 422, 1889.

CHAPTER XXVIII.

TESTING DYNAMOS AND MOTORS.

TESTS to be applied to dynamos are of two kinds, viz. those which relate to the design and construction of the machines, and those which relate to their performance. Under the former are included tests of the resistance of the various coils and connexions, and of the insulation of the working parts. Under the latter are comprised the tests of efficiency under various loads, and of output at different speeds and conditions of working.

Testing Construction.—The resistance of the various parts of the armature coils, of the field-magnet coils, and of the various connexions, may be tested in the ordinary manner, by means of a Wheatstone's bridge, or by one of the recognized galvanometer methods. The only point of difficulty lies in measuring such small resistances as those of armatures and of series coils, which are often very small fractions of an ohm. In this case probably the best method of proceeding is the following. By means of a few cells of accumulators send a strong current through the coil or armature whose resistance is to be measured, interposing in the circuit an amperemeter. While this current is passing, measure, by means of a sensitive voltmeter, the fall of potential between the two ends of the coil. By Ohm's law, the number of volts of fall of potential divided by the number of amperes of current will give the resistance in ohms. Additional accuracy may be secured by connecting in the circuit a strip of stout German silver, as recommended by Lord Rayleigh, of known resistance, and comparing the fall of potential between the two ends of the strip with the fall of potential in the coil. The ratio of the two falls of potential will equal the ratio of the resistances.

It ought on no account to be forgotten that the internal resistance of a dynamo when warm after working for a few hours is considerably higher than when it is cold. Tests of resistance ought therefore to be made both before and after the dynamo has been running. The perfection of the magnetic circuit may be tested in two ways. If the design or construction of the magnetic circuit is such as to give rise to magnetic leakage, it is desirable to ascertain the proportion of leakage. The actual amount of magnetic leakage may be measured by placing exploring coils over different parts of the magnetic circuit in the manner used by J. and E. Hopkinson. They passed a single convolution of wire around the magnet-frame at different points, and joined it to a suitable galvanometer. The throw imparted to the galvanometer when the current in the magnetizing coil was suddenly turned off or on, is a measure of the number of magnetic lines enclosed by the exploring coil. The other way of examining the perfection of the magnetic circuit is to join up a known suitable resistance to the terminals of the machine, and then to run it at a slow speed, gradually increasing the number of revolutions until it excites itself. (The method is of course inapplicable to many alternate-current machines.) The least speed of self-excitation is, *cæteris paribus*, a measure of the goodness of the magnetic circuit.

Testing Insulation-Resistance.—It was formerly the fashion to test the insulation-resistance between the coils of a dynamo and its metal cores or frame by using a Wheatstone's bridge and a couple of small cells. The results were supposed to be good if the test came out at a million ohms or more. All such tests are fallacious, as they afford not the slightest evidence as to whether the insulation is likely to break down under the working electric pressures. It must not be forgotten that the electric tension or stress to which the dielectric is subjected, tending to pierce it, varies as the square of the volts. The only rational mode of testing the insulation is to apply a high voltage—say from 2000 to 4000 volts—and see whether the insulation resists being pierced. The most convenient way of applying the test is to use a small alternate-current transformer, giving the requisite voltage. All dynamos, motors, and transformers intended for high voltage work should be tested at double the volts which they are intended to work at. All tests should be made when the apparatus is warm after having been used.

Testing Performance and Efficiency.—The testing of the efficiency and working capacity of a dynamo, whether working as generator or as motor, is a more serious matter, and involves both electrical and dynamometrical measurements.

In the case of the dynamo-generating currents, measurements must be made (*a*) of the horse-power expended, and (*b*) of the energy of the electric currents realized.

In the case of the motor doing work, measurements must be made (*a*) of the electric energy consumed, and (*b*) of the mechanical horse-power realized.

Measurement of Horse-power.—There are four general methods of measuring mechanical power :—

(*a.*) *Indicator Method.*—By taking an indicator diagram from the steam-engine which supplies the power.

(*b.*) *Brake Method.*—By absorbing the power delivered by the machine, at a friction brake such as that of Prony, Poncelet, Appold, Raffard, or Froude.

(*c.*) *Dyamometer Method.*—By measuring in a transmission dynamometer or ergometer, such as that of Morin, von Hefner-Alteneck, Ayrton and Perry, or of F. J. Smith, the actual mechanical power of the shaft or belt.

(*d.*) *Balance Method.*—By balancing the dynamo or motor on its own pivots and making it into its own ergometer.

To these must now be added a fifth method, namely :—

(*e.*) *Electrical Method.*—By making the motor drive the dynamo which supplies it, measuring electrically the work given out in the one, or absorbed by the other, and then measuring, either mechanically or electrically, the difference.

(*a.*) *Indicator Method.*—The operation of taking an indicator diagram of the work of a steam-engine is too well known to engineers to need more than a passing reference. This method is, however, not always applicable, for in many cases the steam-engine has to drive other machinery, and heavy shafting for other machinery. In such cases the only remedy is to take two sets of indicator diagrams, one when the dynamo is at work, the other when the dynamo is thrown out of gear, the difference being assumed to represent the horse-power absorbed by the dynamo.

(*b.*) *Brake Method.*—The friction-brake of Prony is well known to engineers, but the same can hardly be said of the more recent forms of friction dynamometers. Various improvements have been introduced in detail from time to time by Poncelet, Appold, and Deprez. In Prony's method the work is measured by clamping a pair of wooden jaws round a pulley on the shaft; the torque on the jaws being measured directly by hanging weights on a projecting arm with a sufficient moment to prevent rotation. If p is the weight which at a distance l from the centre balances the tendency to turn, then the friction-force f multiplied by the radius r of the pulley will equal p multiplied by l.

This may be written,

$$\text{Torque} = f\,r = p\,l.$$

From which it follows that

$$f = \frac{p\,l}{r}.$$

If n be the number of revolutions *per second*, then $2\,\pi\,n$ is the number of radians per second, or in other words, the angular velocity for which we use the symbol ω, and $2\,\pi\,n\,r$ is the linear velocity v at the circumference. Now the work per second, or power, is the product of the force at the circumference into the velocity at the circumference, or

$$w = f\,v = \frac{p\,l}{r} \,.\, 2\,\pi\,n\,r = 2\,\pi\,n\,p\,l.$$

If p is measured in pounds weight, and l in feet, then, remembering that 550 foot-pounds per second go to one horse-power, we have

$$\text{Horse-power absorbed} = \frac{2\,\pi\,n\,p\,l}{550};$$

or, if p is expressed in grammes weight, and l in centimetres, it must be divided by $7 \cdot 6 \times 10^6$ to bring it to horse-power.

The later improvements imported into the Prony brake are of great importance. Poncelet added a rigid rod at right angles to the lever, and attached the weights at the lower end. Appold substituted for the wooden jaws a steel strap, giving a more equable friction, and therefore having less tendency to vibration. Raffard[1] substituted a belt differing in breadth, and therefore offering a variable coefficient of friction, according to the amount wrapped round the pulley. Further modifications of this kind of brake dynamometer have been made by Professor James Thomson, Professor Unwin, M. Carpentier, and by Professors Ayrton and Perry. The friction of a turbine wheel was also applied as a dynamometer brake by the late W. Froude.

As all these brake dynamometers measure the work by destroying it, it will be seen that though they are admirably adapted to measure the work furnished by a motor, they cannot, except indirectly, be applied to measure the work supplied to a dynamo. Some experience in working with these machines is essential if reliable results are to be obtained; but with the more modern forms of instrument, such as those of Poncelet and Raffard, the results are very good. The great secret of success is to keep the friction surfaces well lubricated with an abundant supply of soap and water.

(*c.*) *Dynamometer Method.*—The Prony brake was styled above a brake dynamometer; but the true dynamometer for measuring transmitted power does not destroy the power which it measures. Transmission dynamometers may be divided into two closely allied categories: those which measure the power transmitted along a belt, and those which measure power transmitted by a shaft.

In the case of transmitting power by a belt, the actual force which drives is the difference between the pull in the two parts of the belt. If F' is the pull in the slack part of the belt before reaching the driven pulley, and F the pull in the tight part of the belt after leaving the driven pulley, then $F - F'$ represents the nett pull at the circumference, and $(F - F') \times r$ is the torque T. Then if n is the number of revolutions *per second*, the angular velocity ω will be equal to $2 \pi n$. This gives us as the work per second, or power,

$$w = \omega T = f v = 2 \pi n r (F - F').$$

As before, if F is expressed in pounds weight and r in feet, the expression must be divided by 550 to bring to horse-power: or must be divided by $7 \cdot 6 \times 10^6$ if the quantities are expressed in grammes weight and centimetres.

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[1] For further accounts of these instruments the reader is referred to Weisbach's *Mechanics of Engineering;* Spons' *Dictionary of Engineering*, Article "Dynamometer"; Smith's *Work-measuring Machines;* a series of articles in the *Electrician*, 1883–4, by Mr. Gisbert Kapp; *Proc. Inst. Mech. Eng.*, 1877, p. 237 (Mr. Froude); *Rep. Brit. Assoc.*, 1883 (Prof. Unwin); *Journ. Soc. Telegr.-Eng. and Electr.*, xlix., vol. xii. 346 (Profs. Ayrton and Perry).

A dynamometer which can be applied to a driving belt, and actually measures the difference F − F′ in the tight and slack parts of the belt, has been designed by von Hefner-Alteneck, and is commonly known as Siemens' dynamometer.[1] Other forms have been devised by Sir F. J. Bramwell, W. P. Tatham,[2] W. Froude, T. A. Edison, and others. Nearly all of these instruments introduce additional pulleys into the transmitting system, causing additional friction.

Much more satisfactory are those transmission dynamometers which measure the power transmitted by a shaft. In nearly all instruments of this class there is a fixed pulley keyed to the shaft, and beside it a loose pulley connected with it by some kind of spring arrangement, so set that the elongation or bending of the spring measures the angular advance of the one pulley relatively to the other; this angular advice is proportional to the transmitted torque. To this class of instrument belongs the well-known dynamometer of Morin, in which the displacement of the loose pulley is resisted by a straight bar spring, the centre of which is attached to the driving shaft. Modifications of the Morin instrument have been devised by Easton and Anderson, Heinrichs,[3] Ayrton and Perry,[4] Murray,[5] and the Rev. F. J. Smith, of the Millard Engineering Laboratory, Oxford. Of the last-named instrument, a full description and cut were given in the former editions of this book.

(*d.*) *Balance Method.*—The following method was devised by Mr. Smith when testing some small Trouvé motors at the Paris Exposition of 1881. With small motors there arises the difficulty that the ordinary means of measuring the work they perform introduce relatively large amounts of extraneous friction. The motor to be tested is placed with its armature spindle between centres, or on friction wheels, and the weight of the field-magnets and frame is very carefully balanced with counterpoise weights. In Fig. 494, B D represents the field-magnets and frame of the motor duly counterpoised, and E is the armature. When the current is turned on, the armature tends to rotate in one direction, and the field-magnets in the other; the angular reaction being of course equal to the angular action. If the reaction which tends to drive the field-magnets round, be balanced by applying a force P (for example that of a spring balance) at the point C of the frame A B C D, then the moment of this force P d measures the torque, exactly as in the Prony brake. Hence it will be seen that the motor has become its own dynamometer, the magnetic friction between the armature and the field magnet being substituted for the mechanical friction between the pulley and the jaws. A modification of the balance method, due to Herman Müller, consists in swinging the dynamo in a cradle, pendulum fashion, from the driving shaft, and estimating the power absorbed by the displacement from the vertical line.

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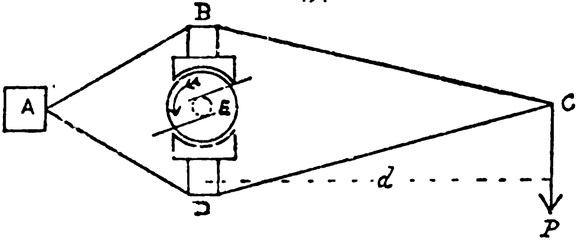
[1] One form of the Siemens dynamometer is described by Hopkinson, *Proc. Inst. Mech. Eng.*, 1879. A more modern form is described by Schröter, *Bayerisches Industrie- und Gewerbeblatt*, 1883.

[2] *Journ. Franklin Institute*, Nov. 1886.

[3] See *Engineering*, May 2, 1884, and *Electrical Review*, April 26, 1884, for an excellent account of a series of tests carried out with great care and ability for Mr Henrichs, by Messrs. Alabaster, Gatehouse and Co.

[4] *Journ. Soc. Telegr.-Eng. and Electr.*, xii. 163, 1883. [5] *Ibid.*, xviii. 1889

FIG. 494.



SMITH'S METHOD OF TESTING MOTORS.

M. Marcel Deprez and Professor C. F. Brackett have proposed to apply the balance method to dynamos in action. Professor Brackett places the dynamo in a sort of cradle, balanced on centres that lie in the axis of rotation, and measures the angular reaction-force or torque between the armature and field-magnets, and multiplying this by the angular velocity $2 \pi n$, obtains the value of the power transmitted to the armature.

All these several dynamometric methods necessitate the use of a speed indicator to count the number of revolutions n, which enters as a factor into the calculation of horse-power. Too great care cannot be taken, especially in testing *small* machines, that no unnecessary friction be thereby introduced. A flexible connexion, such as a piece of dentist's spring, between the axle of the machine and the axle of the counter appears to be desirable. The number of revolutions *per second* n being known, the angular velocity $\omega = 2 \pi n$ can be calculated. This only requires to be multiplied by the torque $T = F r$ to give the power or work-per-second w. And if T is expressed in pound-feet, then,

$$\text{Horse-power} = \frac{2 \pi n F r}{550} = \frac{\omega T}{550}.$$

(*e.*) *Electrical Methods.*—There are several varieties of this modern method of testing, and they involve the use of two, or in some cases three machines. J. and E. Hopkinson[1] propose to use two similar machines, one as generator, the other as motor, connected together both electrically and mechanically. The power given out by the former machine, and that absorbed by the latter, are measured electrically. The motor is made to use its mechanical power to aid in driving the generator, and the small additional power required to drive the generator (supplied by a steam-engine) is measured mechanically by a dynamometer. Modifications of this method for the purpose of obviating all mechanical measurements have been suggested by Lord Rayleigh,[2] Captain Cardew,[3] whose method dates from 1885, M. Menges,[4] Mr. Ravenshaw,[5] Mr. Swinburne, and Mr. Kapp.[6]

All these methods are far more accurate than the rough mechanical methods of earlier date, and each has its advantages, but Hopkinson's method requires two similar machines, and Cardew's requires three machines, one of which must be powerful enough to run the other two. In Swinburne's method the loss of power due to resistance of conductors is calculated, and this deducted from the whole loss of power in the machine gives the "stray power" made up of losses due to eddy-currents, friction, and magnetic hysteresis, which are thus measured together. This stray power is determined by using the machine as a motor, the field-magnets being separately excited so that the armature has the same magnetic induction as at full load, the electromotive-force applied to it being such as to drive it at its normal speed. Only a small generating dynamo is required to furnish the current for this. When matters are so arranged that the machine to be tested runs at its normal speed, the power used in driving the machine (which is measured electrically by taking readings of the volts on the armature and the amperes flowing through it, and multiplying up) is equal to the stray power at full load.

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[1] *Phil. Trans.*, 1886, ii. 347. See also *Electrician*, xvi. 347, 1886; and *Electrical Review*, xviii. 207 and 230, 1886.

[2] *Electrical Review*, xviii. 242, 1886.

[3] *Ibid.*, xix. 464, 1886; and *Electrician*, xvii. 410, 1886; and xxi. 275, 1887.

[4] *Electrician*, xvi. 371, 1886.

[5] *Electrical Review*, xix. 424 and 437, 1886.

[6] *Ibid.*, xxi. 181 and 215, 1887.

An example may be useful. Suppose we have to test a large 50 kilowatt shunt-wound dynamo, giving 500 amperes at 100 volts at 720 revolutions per minute, and that $r_a = 0{\cdot}006$ ohm, and $r_s = 12$ ohms, the lost amperes will be $100 \div 12 = 8{\cdot}5$, total current say 508 amperes; hence lost volts $508 \times 0{\cdot}006 = 3$ volts; whence E = 103 volts. Watts lost in armature $= 508 \times 508 \times 0{\cdot}006 = 1548$. Watts lost in shunt coil $= 100 \times 100 \div 12 = 833$. Now arrange any small dynamo, of say 2 H.P., to give out current at 103 volts; and from this run the large dynamo that is to be tested, as a motor, with no other load than its own friction, hysteresis and eddy-currents. It will run under 720 revolutions, since with such small current its armature produces no demagnetizing action to quicken it up. Therefore add some resistance to its shunt till it comes up to speed. Then measure the current it is taking; this multiplied by E gives the stray power. Suppose it takes 9 amperes, then the stray power is $103 \times 9 = 927$ watts. We may at once reckon out the efficiencies. The losses now known are $1548 + 833 + 927 = 3308$. Add this to the 50,000 watts of nett out-put, and we get the gross out-put 533,08. Hence we have the following:—

$$\text{Gross efficiency} = \frac{52381}{53308} = 98{\cdot}3 \text{ per cent.}$$

$$\text{Electrical efficiency} = \frac{50000}{52381} = 95{\cdot}5 \quad \text{,,}$$

$$\text{Nett efficiency} = \frac{50000}{53308} = 93{\cdot}8 \quad \text{,,}$$

Testing Separate Losses.—In the preceding paragraph no distinction was made between the three sources of loss which go to make up the stray power, namely, friction, eddy-currents, and hysteresis. It was indeed possible to separate the eddy-current loss from the others by making experiments at different speeds,[1] because the eddy-current loss increases proportionately to the square of the speed, whilst the other losses are approximately proportional simply to the speed. The power thus wasted was given to the armature by a motor, and measured electrically. In 1891 a method of separating these losses was independently published by Kapp[2] and by Housman.[3] From the latter's paper are taken Figs. 495 and

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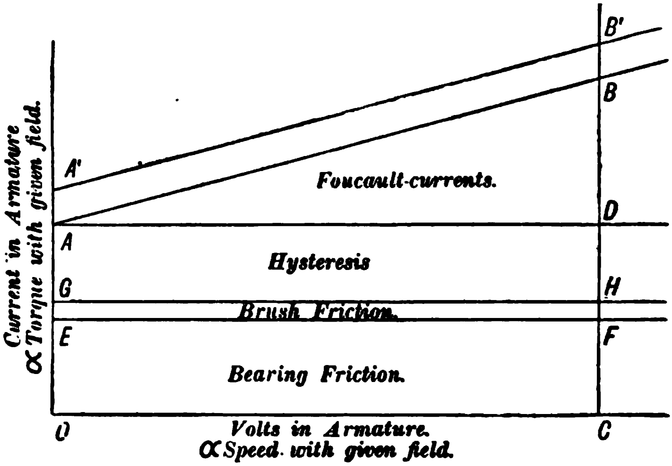
[1] *Journ. Inst. Electrical Engineers*, xviii. 620, 1889.

[2] *The Electrician*, xxvi. 699, 1891.

[3] *Ibid.*, xxvi. 700, 1891; also *Journ. Inst. Electrical Engineers*, xx. 298, 1891.

496, which show the method adopted by both these engineers. The method is as follows :— Let the field-magnet be separately excited to a constant value. Then measure the currents required to run the armature as a motor with no load at different speeds, by using different volts. The results when plotted out as a curve give a straight line A B, Fig. 495 cutting the axis of current above the origin. A horizontal line, A D, through A, divides the ordinates, such as C B, into two parts; one C D, which represents the losses that are proportional to speed; and another D B which represents those that are proportional to the square of the speed. To separate friction of bearings and brushes, the armature should be coupled direct to another similar machine, the latter running without excitation of magnets, when the increase of current needed to drive will give a measure of frictional loss, and from this the lines E F and G H may be plotted out. If a second set of observations are made with a field of different strength, a second line A′ B′ will be obtained, which will be above or below A B, according to whether the change of field has increased or diminished the total losses. The minimum total

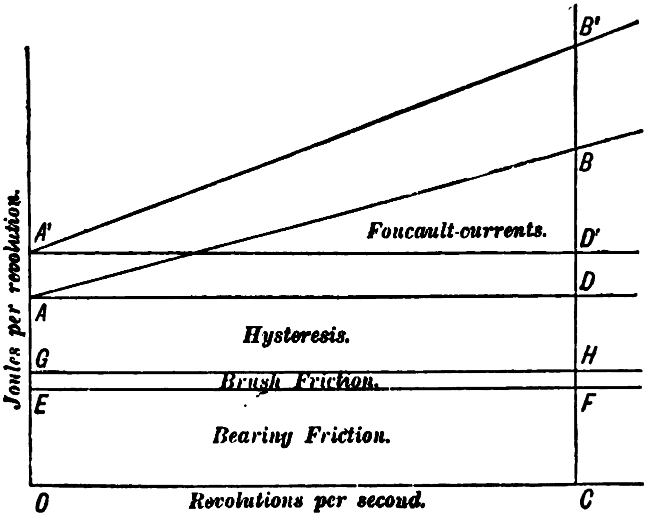
FIG. 495.



SEPARATION OF LOSSES IN DYNAMO.

loss usually occurs with an excitation that makes B in the armature about 15,000 or 16,000; for when the excitation is pushed further, not only does hysteresis become much greater, but the eddy-currents in shaft and pulley, due to the leakage of magnetic lines, are greater. If the curve A B curves upwards at the higher values, it shows that the eddy-currents in the armature are producing perceptible demagnetization. In Fig. 496 the values plotted have been changed from electrical to mechanical values, so as to permit of a single scale being used for experiments with various degrees of excitation.

FIG. 496.



SEPARATION OF LOSSES IN DYNAMO.

Mr. Kapp has communicated to the author a method of testing which permits the commercial or nett efficiency to be determined electrically with far higher accuracy than is possible with any mechanical dynamometer. It requires two machines of nearly equal power, one to run as generator, the other as motor, together with a small auxiliary machine of normal voltage, to which the other two are coupled in parallel. If the machine to be tested is called A, and its fellow B, we may call the small dynamo C. The armatures of A and B must also be coupled together mechanically, and the field of B must be weakened by use of a rheostat, so that it may run as a motor. C gives the current necessary for exciting and for making up the difference between the currents in A and B. Insert an amperemeter from one brush of A to one of B, to measure the current flowing from one to the other, and let two readings be taken when the current from C is introduced first at the terminals of A, then at those of B. The volts are the same in each case. Hence the ratio of the two currents is the efficiency of the combination of the two machines; and the square-root of the ratio of the two readings is the efficiency of either machine.

An elaborate arrangement of speed-cones for dynamo testing, designed by Prof. Ayrton, is described in *Industries*, June 22, 1888. For detailed account of tests on dynamos the reader is referred to the following sources:—*Report of Committee of Franklin Institution*, 1878; *Crystal Palace Exhibition* 1882, *Report*, by Lieut. F. J. Sprague, United States Commissioner; also see the Inaugural Address of Prof. W. G. Adams in *Journal Soc. Telegr.-Engin. and Electr.*, 1884; Thesis of J. W. Howell on tests made at Stevens Institute, reprinted in a volume on *Incandescent Electric Lighting*, published New York, 1883, by Messrs. Van Nostrand; *Official Report of Munich Electric Exhibition*, 1882; also the tests made by Messrs. Alabaster, Gatehouse and Co., reported in *Engineering*, May 2, 1884, and *Electrical Review*, April 26, 1884; also *Report of Jurors, Cincinnati Industrial Exposition* 1883; also Prof. W. G. Adams' Inaugural Address, *Journal of Society of Telegraph-Engineers and Electricians*, xiv. 4, 1885; also Reports of Electrical Exhibition at Philadelphia 1884, published in *Journal of the Franklin Institution*, 1885; tests of arc-lighting dynamos at Melbourne Exhibition, by K. L. Murray, *Journal Institution Electrical Engineers*, xviii., 1889; tests of dynamos (Desroziers, Edison, Gramme, &c.) at Paris Exhibition of 1889, by A. Minet, *La Lumière Électrique*, xxxv., 1889; tests on Stanley Arc Alternator by Duncan and Hassen, *The Electrician*, xxvi., Jan. 1891; tests of a Goolden dynamo and Willans engine, separating the losses, *ib.* xxvi. 36, 1890; tests of a Wenström dynamo, separating the losses, by Duncan, *Electrical Review*, xxvi, 116, Jan. 1890; papers on Causes of Losses, by Hummel, in *Elektrotechnische Zeitschrift*, viii., 1887, and xii. 1891. At the Frankfort Exhibition of 1891, very careful tests were made of numerous machines under very favourable conditions. None of the results of these tests are yet available down to the hour of going to press.

CHAPTER XXIX.

MANAGEMENT OF DYNAMOS.

This chapter is devoted to three topics:—(1) The coupling of two or more dynamos; (2) General instructions in use of dynamos; (3) The diseases of dynamos.

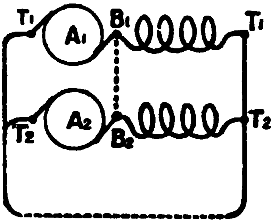
On Coupling Two or More Dynamos in One Circuit.

It is sometimes needful to couple two or more dynamos together so that they may supply to a circuit a larger quantity of electric energy than either could do singly. Thus it may occur that two dynamos, neither of which can safely carry a greater current than 1000 amperes, are required to supply jointly a 2000-ampere current: or two machines, each of which can run at 60 volts, are required to furnish an electromotive-force of 120 volts. Simple as these cases may seem, it is not so easy to carry them out, because it depends upon the construction of the machine, and especially upon the mode of excitation of the field-magnets, whether they can be coupled together without interfering with each other's running. For it may, and does, occur that if not rightly arranged, one machine will absorb energy from the other and be driven as a motor instead of adding anything to the energy of the circuit.

Coupling Machines in Series.—Series-wound dynamos may be united in series with one another for the purpose of doubling the electromotive-force. Thus two Brush machines, each working at 10 amperes, and each capable of working 6 arc-lamps, may be joined in one circuit with 12 arc-lamps in series. The only needful precaution is to see that the + terminal of one machine is joined to the − terminal of the other, precisely as with cells of a battery. Shunt-wound dynamos may also be coupled in series, though the arrangement is not good unless the two shunt coils are also put in series with one another, so as to form one long shunt across the circuit. Compound-wound dynamos may be connected in series with one another, provided the shunt parts of the two are connected as a single shunt, which may extend simply across the two armatures (double short-shunt), or may be a shunt to the external circuit (double long-shunt), or may be a mixture of long and short shunt. The same considerations apply to more than two machines. The coupling of alternate-current dynamos is considered in Chapter XXII.

Coupling Dynamos in Parallel.—Two series dynamos cannot be coupled in parallel in a circuit without a slight re-arrangement, otherwise they interfere. For, suppose one of them to fall a little in speed, so that the electromotive-force of one machine is higher than that of the other machine with which it is in parallel, the machine having the higher electromotive-force will then drive a current in the wrong direction through the other machine, reversing the polarity of its field magnets and driving it as a motor. To obviate this, Gramme made the suggestion that the machines should be coupled in parallel at the brushes as well as at the terminals. This is shown in Fig. 497. The terminals T_1 T_1 of one machine are respectively joined to T_2 T_2 of the second machine, and a third wire joins B_1 with B_2. If both machines are doing precisely equal work, there will be no current through the wire B_1 B_2. If either machine falls behind, part of the current from the other machine will flow through B_1 B_2 and help to maintain the excitement of the magnets of the weaker machine. This effectually prevents reversals.

FIG. 497.



COUPLING OF TWO SERIES DYNAMOS IN PARALLEL.

In the case of shunt machines there is no great difficulty in running them in parallel, as indeed is done on a large scale every day in central lighting stations. The chief precaution to be taken is that, whenever an additional dynamo has to be switched into circuit, its field must be turned on, and it must be run at full speed before its armature is switched into connexion with the mains, otherwise the current from the mains will flow back through it and overpower the driving force.[1] Another method of coupling two series machines is to cause each to excite the other's field magnetism. This equalizes the work between the two machines.

Coupling of Compound Dynamos in Parallel Circuit.—In working compound dynamo machines in parallel circuit, some difficulty has been found, because if for any reason the current from any one machine increases the exaltation of the field strength in such a case, due to the increase of the current traversing the series circuit, raises the electromotive-force of the machine, and causes it not only to do more than its due share of the work, but even to send a back current through the machine which is connected with it, which on account of its reduced electromotive-force becomes merely a part of the external circuit of the more powerful generator. There is no doubt that such an action may take place; and if unavoidable would render compound dynamos unsuitable for employment in many situations where their self-regulating powers must render them very useful. Mr. Mordey first pointed out that the difficulty might be overcome by connecting the parallel machines in such a way that not only are the shunt portions of the field magnets in parallel circuit, but the series circuits of the field magnets are also a shunt on one another; in other words, by connecting the brushes, as well as the terminals, in parallel circuit, precisely as Gramme has done for series-wound machines. This mode of connexion is shown by the accompanying diagram (Fig. 498).

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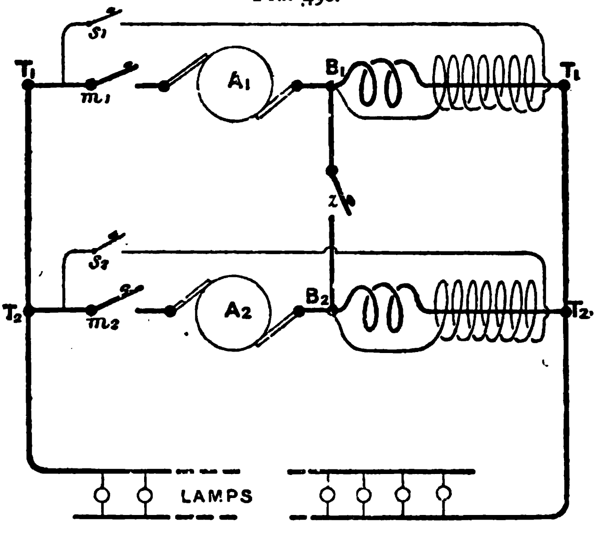
[1] See Burstyn, in the *Zeitschrift für angewandten Elektricitätslehre*, 1881, p. 339, also Schellen (2nd Edition), p. 717; Ledeboer, in *La Lumière Électrique*, xxvi. 210, 1887; Meylan, in *La Lumière Électrique*, xxvi. 379, 1887; and Feussner, in *Zeitschrift für Elektrotechnik* (1887), 108. See also the special mode devised by S. S. Wheeler, U.S. Patent, No. 335,048 of 1886.

FIG. 498.



COUPLING OF TWO COMPOUND DYNAMOS IN PARALLEL.

A_1 A_2 are the armatures of two compound dynamos, T_1 T_1 and

$T_2 T_2$ are the terminals; the wire $B_1 B_2$ acting in conjunction with the lead $T_1 T_2$ on the left, puts the armatures in parallel. When compound dynamos are connected in this way,[1] they work quite satisfactorily, and exercise a considerable power of mutual adjustment. No necessity exists for driving by clutch or other positive connexion, ordinary belt driving being quite admissible, even when the belts have different percentages of slip—as may happen when they are not alike in tightness or character.

This mutual adjustment extends also to the case of slight differences in the sizes of the driving or driven pulleys where a single steam-engine or other motor is driving both or all of the machines, as well as to the case of separate engines being employed to drive separate machines. Of course the power of mutual adjustment must not be unduly strained by trusting to it to remedy inequalities of a serious nature.

The *rationale* of this adjustment is very simple. Taking the case of two exactly similar compound dynamos, connected as described above, it will be evident that as the shunt fields as well as the series fields are similar, and are respectively in parallel circuit, the strength of the magnetic fields in the two dynamos will be alike. Then at the same speed their electromotive-forces will be equal, and they will absorb power equally, and will do equal work. But if from any cause one of them begin ever so slightly to lag behind the other in speed, its electromotive-force will become slightly lower, and it will absorb proportionately less power. The power being thus unequally distributed, the slow machine will tend to race, while the fast one will tend to slow down. In this way the two dynamos will exercise a continual mutual adjustment, resulting in an equal division of the work between them.

And not only does this control exist with similar compound dynamos, but it may be relied on when the dynamos are unlike in size, power, and speed.

For instance, large and powerful machines may be worked in parallel circuit with smaller machines of various power, and each will do its proper share of the work.

In such a case, however, it is necessary to observe an additional precaution. Not only should the various dynamos be connected together, and to the external circuit, according to the plan described above, but such a proportion should be observed between the resistances of the series coils of the various connected machines that with the varying resistance of the external circuit the fall of potential in all the series coils may be similar. This is the case when the respective resistances of the series coils are inversely proportional to the full (or any equal proportion of the full) current intended to be generated by each dynamo.

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[1] The method proposed by M. Ledeboer in *La Lumière Électrique*, xxvi. 210, 1887, is practically identical with the above.

When the resistances of the series fields of the parallel dynamos are thus inversely proportional to their currents, they will work satisfactorily in parallel circuit, and will possess the desired power of adjustment under any circumstances likely to arise in practice where ordinary care and skill are exercised.

The examination of the subject does not, of course, cover all the details of the actions connected with the working of compound dynamos in parallel circuit. A fuller inquiry reveals a theoretical necessity for giving an exactly similar formation to the characteristic curves of all the connected machines. For practical purposes, however, the foregoing precautions will generally be found sufficient.

A method of connecting the machines, differing from the above, has been suggested. It is very similar to that which has been used, as mentioned above, with Gramme dynamos, consisting in employing the current of one machine A to excite the fields of a second machine B, while the current of B in turn is made to magnetize the fields of A. This is a perfectly practicable plan. With compound dynamos the series coils will alone require to be operated in this way. But there are some objections to such an arrangement. It can only be used when the dynamos are exact copies of each other, and is therefore out of the question when it is desired to utilize machines of various sizes and speeds to operate one circuit. Another objection is that with such a method it is always necessary to have at least two machines working, even when one is sufficient or more than sufficient for the requirements of the moment. In such a case, when it may be desired to use one machine only, an arrangement of switches, always more or less unsatisfactory, must be adopted; while the making of the involved change could scarcely be effected, while the machines were working, without causing some interruption to the external current—an event, however momentary, to be carefully avoided in practical work. Again, an accident to one machine would incapacitate not only that machine, but also the second one which relied on the former for its field excitation.

The plan suggested by Mr. Mordey appears the more satisfactory one, and may be used in a lighting station, or in any situation where the varying requirements of the circuit render it desirable to bring additional machines into operation as the work increases, and to disconnect them from the mains as the demand for current falls off. To accomplish this the following arrangements and order of operations should be observed. The dynamos should each be furnished (see Fig. 498) with a switch s in the shunt circuit; they should each have also a switch m in their main circuit between the armature part and the point where the shunt circuit joins on, so that the armature part may be interrupted without interrupting the shunt circuit. The connecting wire from brush to brush, which should be at least as thick as the mains, should also be furnished with a switch z. Suppose dynamo No. 1 is at work alone, its two switches, s_1 m_1, will be closed. If, now, dynamo No. 2 is to be thrown in, the following order must be observed. First get up the speed of No. 2 to its full value, then close s_2, then z; this will fully excite its magnetism; lastly, close m_2. When No. 2 has to be thrown out of circuit the order must be exactly reversed: first open m_2; then z; then s_2; lastly, slow down the machine. A special combination-switch, which will perform these successive operations in their proper order, is desirable.

The coupling of alternators has been specially considered in Chapter XXIII.

GENERAL INSTRUCTIONS IN USE OF DYNAMOS.

Position of Dynamo.—The place chosen should be dry, free from dust, and preferably where a cool current of air can be had. It should allow a sufficient room for a belt of proper length, unless the dynamo is direct-driven.

Foundations.—It is most important to secure good foundations for every dynamo; and if the dynamo is direct-driven, but is not on the same bed-plate as the engine, a foundation large enough for both together should be laid down. Stone or concrete may be used, or brick built with cement, having a large thick stone bedded at the top. For small dynamos the holding-down bolts may be set with lead or sulphur in holes in the stone top; but for large dynamos the bolts should be long enough to pass right down to the bottom, where they should be secured into iron plates built in. If long holes are left in the foundations for the holding-down bolts, they should be filled in with thin cement after the latter have been put in place.

Sliding Rails.—All belt-driven dynamos ought to be provided with tightening gear to take up the slack. If the dynamo is not provided with sliding rails under its bed-plate and tightening screws, the less desirable method of employing a tenting pulley, as in Plate XX., may be used. In any case the bed for dynamo must be quite level, and the shaft set properly parallel with the driving pulley.

Before Starting.—Examine the dynamo before it is set running for the first time. Remove caps of bearings and clean them and the journals. Replace them, but do not screw up too tightly. See that lubricators are filled, and the drip properly adjusted. Use *copper* oil-cans. Turn the armature round by hand to see that nothing catches, and no loose wires or waste are adhering to it. Clean up the commutator with the finest emery cloth, and note carefully that no dirt or copper-dust is lodged between the bars of the commutator. A stiff dry hog-brush will be useful here. See that the brush-holders work rightly, and that the hold-off catches, if any, are in order. See that each brush is properly trimmed (*i. e.* filed off at the proper bevel at the ends. Some makers provide a special tool to guide the file at the proper angle). Adjust the brushes, first, by clamping them *very firmly* in their holders, so that they protrude to the proper length. (For this purpose many makers provide each holder with a pointer, as at P on Plate III.). Adjust them, secondly, so that they bear with a moderate but firm pressure on the commutator. See, thirdly, that when so pressing, they bear in the right positions. For two-pole dynamos the brushes should bear on precisely opposite bars of the commutator. For four-pole dynamos they bear on bars that are a quarter of the circumference apart. (It is customary for makers to mark two of the commutator bars with a centre-punch so that this adjustment may be verified). Then, having verified these adjustments, raise the brushes out of contact until you have started running. Wherever a single dynamo is driven from an engine it is well that the brushes should be only lowered after starting running, and raised before stopping running, so as to avoid all chance of the brushes being spoiled by the dynamo turning in the wrong direction. But the current should always be turned off before a brush is raised, otherwise a destructive spark will spoil the commutator.

The brushes being adjusted and lubricators filled, see that the connexions are right, the terminals tightly screwed down. Then begin running with brushes raised out of contact and main-switch open, just to see that all is right mechanically, and that the bearings do not heat. Then let down the brushes. If the machine is shunt-wound it will at once excite itself, though the main-switch is still open. If the dynamo is for supplying glow-lamps, do not on any account turn on the main-switch until you see whether the machine is giving the right volts, or you may ruin all your lamps. For if the speed is too high, the volts may be too high. A pilot lamp or a voltmeter will tell you if all is right. Then, before you turn on the main-switch, observe the brushes to see if there is any sparking. If there is any sign of sparks, rock the brushes forward or backward till a sparkless place is found. Not until then should the main switch be turned and the lamps lit.

Daily Attention.—Beside daily lubrication, attention must be given to the brushes to see if they require to be fed forward or trimmed. The commutator should not be oiled, but only wiped with an oily rag or a piece of cotton cloth (*not* waste) smeared with vaseline. (This reservation does not apply to arc-light dynamos with special commutators with wide air-gaps like those of the Thomson-Houston machine, which may be oiled freely.) If the dynamo is driven from heavy shafting, so that there is no risk of turning backwards at starting or stopping, then the brushes may always be left down on the commutator. Many dynamos will spark at full load unless the brushes are rocked forward beyond the point that gave sparkless running an open circuit. Sparkless running is a vital matter if the commutator is to last long. The attendant cannot be too strongly impressed with the necessity of proper care on this matter. A well-designed modern dynamo, if properly attended to, will soon acquire a beautiful dark-polished surface on its commutator. But the commutator, even of a good machine, may be ruined in a few hours by careless or ignorant handling. If the brushes press too heavily, it will become scored or ploughed up. If they press too lightly, or if there is vibration that causes them to jump, or if they are allowed to spark, the commutator will be worn away in patches at the edges of some of the bars, and lose its cylindricity of outline. The only remedy in this case is to carefully turn it or file it down true; and this should occur very rarely.

DISEASES OF DYNAMOS.[1]

At least four-fifths of the mishaps and break-downs that occur with dynamos arise from causes more strictly within the province of the engineer than in that of the electrician. On the other hand, many of the mechanical faults that develop themselves in the machine might have been avoided had the engineer been possessed of a better knowledge of the electric and magnetic conditions which obtain in the running of the machine. It is not often nowadays that armatures fly to pieces. That disaster has seldom occurred since good engineers took in hand the construction of dynamos. The points which it is difficult for the ordinary engineer to grasp are the circumstance that it is on the copper conductors rather than on the iron cores that the drag and stress of the magnetic field is exerted, and the necessity throughout of preserving proper insulation. All insulation being mechanically bad, he is apt, in attempting to give mechanical strength, to use the insulating materials in some way that vitiates their adequacy. For want of full electrical information he may apply the insulation in an erroneous manner and produce a dynamo which will break down under the severe conditions of actual work.

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[1] See paper by the author in *The Electrician*, xx. 82, 1887; see also articles in *Electrotechnische Zeitschrift*, xi. 186, 1890; *Electrical World*, xiv. 99, 184, and xviii. 383, 1891.

Burning-out of Armatures.—Single coils of an armature sometimes get heated to redness and burn the insulation. Sometimes a whole armature will become overheated, producing a general charring. The latter case happens more often to the armatures of motors than to those of dynamos. For if any excessive current is drawn by accident from a dynamo, the torque on the armature will generally become so great as to throw off the belt or pull up the engine. Whereas, with a motor, if the armature is jammed so that it cannot turn, an enormous current will continue to flow through it if the supply be not cut off. The burning of a single coil or section of the winding is sometimes due to short-circuiting at the commutator between two adjacent bars; but more often it is due to short-circuiting in the armature itself. In drum armatures, and in those forms of ring armature which are so connected that the windings cross over one another, this evil may occur in consequence of the abrasion of the insulation. In the old wire-wound drum armatures short-circuits were frequent, from the overwrapping of the ends of coils of widely-different potentials. Short-circuit between an imperfectly insulated wire and the iron core beneath it is again a fruitful source of trouble. Not that any *one* such contact can of itself produce any effect: but that if there is one such contact, then, if a fault occurs anywhere in the lamp circuit, there will at once be developed a serious leak through earth. Also the risk of shock to persons casually touching any part of the circuit is greater if there is any single fault in the dynamo. Some firms—chiefly American[1]—prescribe that the dynamo frame itself should be insulated from the ground. This is an absurdity for any dynamos except those working at high voltage. The author's experience leads him, on the other hand, to prescribe that the framework of the dynamo should, on the contrary, be carefully connected to earth. If this is done, the risk of accident to attendants—which is considerable in the case of high-voltage machines insulated from their bed—is reduced to a minimum. A contact between an armature conductor and the iron core may occur because of the iron laminæ becoming loose and wearing through the layers of insulation. If the insulation is not waterproof and has got wet, it may break down when the machine is run. Sometimes armatures are destroyed by the burning of the insulation, by the overheating, not of the conductors, but of the iron core. In such cases either the core has not been properly laminated, or else the insulation between the core-discs is defective. The burning of binding wires, which occasionally occurs, is due to want of compliance with the sufficient and necessary electrical conditions. Mica alone, in slips, under the binding wires is insufficient, as it is apt to be slowly ground to powder. It should be placed between strips of some other material, such as vulcanized fibre, as a mechanical backing.

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[1] The lightning arresters used on many dynamos in the States are themselves a source of mishaps. If the dynamo frame is properly earthed there is no need of a lightning arrester on the dynamo. Efficient lightning arresters should be fixed outside the dynamo-house where the overhead circuit enters it.

Being pieces of running machinery, dynamos are liable, as all engines are, to heating of bearings, if proper attention is not paid to lubrication and to the avoidance of needless dirt.

Fracture of Connexions.—This most annoying fault—the fracture of the connecting pieces which lead down from the armature conductors to the bars of the commutator—appears to be partly mechanical and partly electrical. These connecting pieces pass through a partial magnetic field, and they carry at times strong currents, which are reversed twice in each revolution. Hence they are each racked by lateral forces as they rotate, and this incessantly repeated breaks them off at last. The cure is either to make them mechanically very strong, or of stranded material, or to arrange that they shall lie outside the waste field.

Disconnexions in Armature.—Sometimes a disconnexion occurs where the armature conductors or windings are coupled up or connected down to the commutator. The evidence of this is (i) a sparking that cannot be stopped by rocking the brushes forward or backward, and (ii) one or more of the bars of the commutator appearing as if burned at the edge. One way[1] of finding the location of such a fault is to run the dynamos on open circuit, that is to say, with the brushes down, but no lamps on. Then after a few minutes' run stop the machine and see if any of the joints of the connectors are hot; this will indicate a partial disconnexion. If any entire coil is found to be hot, that is evidence not of a disconnexion, but of a short-circuit.

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[1] Another way, applicable only to drum armatures, is due to Loomis (*Electrical Engineer*, New York, December 1891), and consists in holding the armature by hand and slowly turning it round against the torque while supplied with a current from some external source. If a position is found where it is easier to turn, it is clear that in this position the disconnexion stops part of the current, so that the fault can at once be found by tracing the connectors which run from those bars of the commutator which are at the brushes in this position.

Flats in the Commutator.—Occasionally one of the commutator segments will become burned away or worn down to a lower level than the rest, or two adjacent bars may be similarly affected, causing a flat part on the cylindrical surface. Various suggestions have been offered to explain the origin of flats. If one of the bars was of unusually soft copper it might wear away faster; but the occurrence is unlikely. A partial disconnexion in the armature at the part connected to the particular bar of the commutator will give rise to a spark here at every half-revolution, so biting away this bar. Flats have been noticed also to spread along the bar from a flaw at one spot.

Another undoubted cause of flats is a mechanically weak or defective means of driving. If an armature, attached by a three-legged spider, is mounted on a weak shaft that bends, it is possible that periodic vibrations may occur which will cause the brushes to jump and set up sparks at definite points around the commutator. With well-constructed armatures, well-balanced and running without vibration, there is little fear of flats if the pressure of the brushes is sufficient. Whenever a bar of the commutator shows signs of burning along its edge, steps should at once be taken to prevent the development of a flat. A fine file should be applied to smooth the surface of the commutator in the neighbourhood of the threatened spot. Or, if need be, the commutator should be very slightly turned down. A narrow tool should be used for this purpose, so as not to drag the copper, and the surface should be polished with very fine Sand paper ~~emery cloth~~ and examined to see that at no spot has the thin strip of mica been bridged over by a burr at the edge of any of the bars.

Faults in Field-magnet Coils.—Sometimes faults occur in field-magnet coils. These may be of two kinds—disconnexions or short-circuits. When there is a disconnexion the machine will probably refuse to excite itself. To make sure, the suspected coil should be disconnected at the ends and tested. A cell of Leclanché battery and a simple detector galvanometer, or, failing this, a common electric bell will suffice to prove whether the wire is continuous. If the frames on which the coils are wound are loose, the resulting vibration may cause the leading-out ends of the wires to snap, perhaps at some point below the surface which can only be reached by unwinding the coil. A short-circuit between any two of the windings will have the effect of keeping the short-circuited part cool whilst the rest of the coils are hot. In a shunt coil, short-circuiting some of the windings causes the rest to overheat dangerously. A short-circuit may arise between the frames or cores and the coils, and may be also tested for by electric bell or detector as above. If there is a single contact fault of this sort between coils and iron-work in the field-magnet, then a single fault at any other point—armature, commutator, brushes, terminals, or circuit—may work dire disaster. Once the author was confronted by a curious double fault which for some time defied detection. In a small Brush arc-light dynamo two single faults occurred at the screws which fixed the iron support that held the rocker for one of the pairs of brushes, with the result that two of the four pairs of coils on the armature were short-circuited.

Faults of Alternators.—Alternators are liable to faults of special kinds. Sometimes they show a regular pulsating flicker, timed exactly to the revolutions of the armature. This can only be due to some double inequality. If one pair of poles of the field-magnet is weaker than the rest, and one of the armature coils is defective, then when these come together in position once in each revolution the current may show a momentary drop. Alternators are usually made for high voltage, and are therefore liable to faults of insulation that might not occur in low-voltage machines. If the two collecting rings are side by side on the shaft, a spark—or rather arc—may spring over from one to the other unless a high projecting washer of ebonite is interposed. The peculiar racking action of the alternating current on the armature coils (see p. 638) is responsible for many failures in this class of machine.

Obscure Causes of Mishap.—Occasionally it occurs that a dynamo fails to give any current. In all such cases the first thing to suspect is that a disconnexion of the circuits has occurred. All terminals and coupling screws should be examined. The lacquer under the head of a terminal screw—where no lacquer ought to be—may be responsible. Dirt between the brushes and their clamps, or between the brush-holder and the brush-holder rod, may be the cause. A shunt-dynamo will not excite its magnets if the main circuit is short-circuited; and a series-wound dynamo will not excite them if the main circuit is open. If all other expedients to get the machine to excite itself fail, try the effect of reversing the connexions that take the current from the brushes to the exciting coils.

Many a mishap has been caused by too free a use of oil, or by oil leaking over from the bearings to the commutator or getting into the armature. Oil is apt to spoil the insulating materials by rotting the varnish, and affording a lodgment for dirt and for the fine copper dust that flies from the brushes. Also, if oil gets to the commutator it will char under the brushes, forming a carbonaceous film between the commutator bars, inviting a short-circuit. This fault is less likely to occur when mica-insulation is used than when asbestos or paper is employed. It has been observed that the brushes wear and heat unequally: the positive brush wearing faster than the negative. But this is unimportant. If there is solder on the brushes, care should be taken that the soldered part should never be used for contact on the commutator: it will set up flashing sparks.

Vibration and Noise.—Excessive vibration can only be due to want of proper balance in the armature. Vibration of a kind that may, nevertheless, be disastrous to the dynamo, racking its conductors, pounding its insulation to dust and causing the brushes to jump and spark, may be occasioned, even in a well-balanced machine, if it is not firmly secured to a proper foundation. Continuous-current machines should run practically silently: the belt will make far more noise than any part of the dynamo. Alternators do not usually run silently, for the coils of all disk armatures churn the air between the poles. If the iron cores of the armature part are subjected to too severe a cycle of magnetization they will emit a loud humming sound, which cannot be cured except by using the machine at a lower degree of excitation, being a defect of design. Once the author came across a remarkable case of an alternator which emitted a sustained howling sound of piercing loudness. The cause in this case was the accidental coincidence between the number of alternations and the natural vibration period of some of the solid iron parts. It was cured by re-fitting the iron parts so as to alter the fulcrum from which the parts could vibrate.

APPENDIX A.

ELECTRIC AND MAGNETIC UNITS.

THE principal units employed by practical electricians, by international agreement, are:—

The *ampere*, or unit of current (formerly called the *weber*);

The *volt*, or unit of electromotive-force.

The *ohm*, or unit of electric resistance.

These three practical units are based upon certain abstract units, derived by mathematical reasoning and experimentally proven laws, from the three fundamental units:—

The *centimetre*, as unit of length.

The *gramme*, as unit of mass.

The *second*, as unit of time.

The system of "absolute units" derived from these is often denominated the "C.G.S." system of units[1] to distinguish it from other systems based on other fundamental units.

Every system of measurement is based upon some experimental fact or law. We can only measure an electric current by the effects it produces. An electric current can (1) cause a deposition of metals from their chemical solutions; (2) heat the wire that it flows through; (3) attract (or repel) a parallel neighbouring current; (4) accumulate as an electric charge that can repel (or attract) a neighbouring charge of electricity; (5) produce in its neighbourhood a magnetic field, that is to say, can exert a force upon the pole of a magnet placed near it, as, for example, in galvanometers. Now any one of these effects *might have been* chosen as a basis for a system of units of measurement, and all of them have been proposed by one authority or another. As a matter of fact, the fifth of them is made the basis in the system now adopted by international agreement; and it is the best because, firstly, it connects the electrical units with the magnetic ones, and, secondly, it is closely connected with the mechanical units, enabling the mechanical values of the electrical quantities to be readily calculated.

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[1] The reader who may desire fuller information about the C.G.S. system of units is referred to Professor Everett's *Units and Physical Constants*.

Taking then the experimental fact that an electric current flowing in a wire can exert a force upon the pole of a magnet placed near it, we have next to define the conditions with the utmost precision. It is found by experiment that the force which is exerted upon the magnet-pole by the current depends on several other things beside the strength of the current: the force is proportional (*ceteris paribus*) (1) to the length of the conducting wire, (2) to the inverse square of the distance between an element of the wire and the pole, (3) to the strength of the magnet-pole. To be very precise then we ought to take (1) a wire one unit in length, (2) bent into an arc of unit radius so that each element of the wire is at unit distance from the pole, (3) and take a magnetic pole of one unit strength. If these things were done, and there was made to flow through the wire a current so strong that it acted on the pole with one unit of force, then a current of such a strength might be taken as a standard of comparison; for a current that was twice as strong would exert two units of force on the pole, and so forth. But in order to be exact we have yet to define what is meant by "one unit of force" and "a magnet-pole of one unit of strength." Here again we have to go to experimental facts, and choose such as will best suit for the purpose of making a consistent system of units.

A force must be measured by one of its effects, such, for example, as these: that it can (1) raise a given mass against the downward pull of the earth; (2) elongate a spring; (3) impart motion to a given mass, or in other words accelerate it. The first of these, which would seem the most natural to select, is rejected because the downward pull of the earth is different at different places, the second because it would acquire awkward definitions of the elastic properties of springs. So the third is chosen, and to make the definition precise, it must be remembered that experiment proves that the velocity of motion which a force imparts to a mass is proportional (1) to the force, (2) to the time during which it is applied, (3) inversely to the mass acted upon. If, therefore, one could get such a force that, if it lasted one second and was made to act on one gramme, it imparted to that mass a velocity of one centimetre per second, then such a force ought to be called the unit of force. This unit has received the name of "one *dyne*." It may be remarked that the downward pull of the earth on a mass of one gramme is sufficient to give it at the end of one second a velocity of about 32 feet per second, or, more exactly, 981 centimetres per second (in the latitude of London); hence it is clear that the pull of the earth on one gramme (what is commonly called the gramme's weight) is equal (at London) to 981 dynes. The pull of the earth on a pound (commonly called the pound's weight) is 444,971 dynes (at London). A pound at the Pole would weigh 445,879, and at the Equator only 443,611 dynes. One dyne is a pull equal to 0·0157, or about $\frac{1}{63}$ of the weight of a grain (at London). Now, as to the unit strength of the magnet-pole or unit of magnetism: a magnet-pole can (1) lift a piece of iron; (2) repel (or attract) another magnet-pole at a distance. The first of these two effects is rejected as a basis for a definition of a unit because the load that a magnet-pole will lift does not depend only on the amount of magnetism at the pole, but on the shape and quality of the piece of iron lifted. For precise definition of the second effect, upon which the definition is based, it must be remembered that experiment has shown that the repulsion of one magnet-pole by another is proportional (1) to the product of the strengths of the two poles, (2) inversely to the square of the distance between them. If, therefore, we choose two similar and equal poles of just such a strength that when placed at unit distance apart they repel each other with unit force, then such poles will possess that amount of magnetism that ought to be called the unit quantity of magnetism.

We may now retrace our steps and build up systematically the units of the C.G.S. system.

The absolute unit of force ("dyne") is that force which, if it acts on one gramme for one second, gives to it a velocity of one centimetre per second.

The unit of magnetism, or unit magnet-pole, is one of such a strength that when placed at a distance of one centimetre (in air) from a similar pole of equal strength it repels it with a force of one dyne.

The absolute unit of current is one of such a strength that when one centimetre length of its circuit is bent into an arc of one centimetre radius, the current in it exerts a force of one dyne on a unit magnet-pole placed at the centre.

The last definition is difficult to realize in practice, and a complete circle of one centimetre radius is more easy to work with than an arc of one centimetre long only. If the radius be more than one centimetre and there be more than one turn of wire, as in most tangent galvanometers, then a formula is necessary. Writing r for the number of centimetres of the radius, the length of circumference will be equal to $2\pi r$. Then writing S for the number of turns of wire in the coil, and i for the strength in absolute units of the current, the formula connecting these with the force (in dynes) exerted by the current on a unit pole at the centre is:—

$$\frac{2\pi r S i}{r^2} = f;$$

whence

$$\frac{2\pi S i}{r} = f.$$

In the case of the tangent galvanometer, the force, instead of being measured directly is ascertained indirectly, by knowing the value (at the place of observation) of the horizontal component of the magnetic field due to the earth's magnetism, commonly represented by symbol H, and measuring the tangent of the deflexion produced on a magnetic needle hung at the centre when the coil lies parallel to the magnetic meridian. In this case $f = H \times \tan\delta$; whence

$$\frac{2\pi S i}{r} = H \tan\delta.$$

From this it follows that if S, r, H, and the tangent of deflexion are known, the strength of the current i will be reckoned by making the following calculation:—

$$i = \frac{r H}{2\pi S} \tan\delta.$$

(The value of H may be taken as 0·18 at London, and of the following values at other places:—Glasgow 0·17, Boston 0·17, Montreal 0·147, Niagara 0·167, Halifax, N.S., 0·159, New York, Cleveland, and Chicago 0·184, Philadelphia 0·194, Washington 0·20, Berlin 0·178, Paris 0·188, Rome 0·24, San Francisco 0·255, New Orleans 0·82, Mexico 0·31, Bombay 0·33.)

Now, the current that is so strong as to fulfil the above definition is far stronger than anything used in telegraphic work, being about as great in quantity as the current in an arc-light circuit. Accordingly *the practical unit* of current is fixed at one-tenth part of the absolute unit, and it is called "one *ampere.*" It follows that the above equation, when i is to be given in amperes, must be altered to

$$i = \frac{10 r H}{2\pi S} \tan\delta.$$

It may further be noted that the current of one ampere strength will cause the deposition in 1 hour of 1·174 grammes, or 18·116 grains of copper in a copper electrolytic cell. It will in 1 hour deposit 4·024 grammes, or 60·52 grains, of silver in a silver cell. The Committee of the Board of Trade in their Report of 1891, while adopting as the abstract definition of the ampere that given above, also add as a secondary or working definition *that an unvarying current which, when passed through a solution of nitrate of silver in water* (in accordance with the specification attached to their Report), *deposits silver at the rate of* 0·001118 *of a gramme per second, may be taken as a current of one ampere.* They add that an alternating current of one ampere shall mean a current such that the square root of the time average of the square of its strength at each instant in amperes is unity. This is what is called in this book (see p. 631) one "virtual ampere."

The other electrical units also require definition. The *electromotive-force* of a battery, or of a dynamo, is only another name for the power which it possesses to drive electricity through a circuit. (Formerly the electromotive-force of a battery was called its "intensity" as a distinction from the "quantity" of current it would furnish.) It is also sometimes called the electric "pressure." As a basis for a unit of electromotive-force any one of the following experimental facts might have been selected. The electromotive-force is proportional, (1) to the current that it sets up in a circuit of given resistance; (2) to the quantity of electricity that it will force as a charge into a condenser of given capacity; (3) to the number of lines of magnetic force cut per second by a conductor moving in a magnetic field. The first of these would do if the unit of resistance were given, but it is more convenient to make this fact the basis of definition of that unit rather than of the unit of electromotive-force; the second is useful for defining the unit of capacity; the third is selected for defining the unit of electromotive-force, and is extremely appropriate for the purpose, as it is the very principle of the dynamo machine. Clearly, that electromotive-force ought to be reckoned as of unit value which is produced by the motion of a conductor cutting across one line of magnetic force in one second. But this involves the preliminary definition of the unit line of magnetic force. This is as follows:—The so-called magnetic lines of force represent by their direction, the direction of the resultant magnetic force in the space through which they pass: the space traversed by magnetic forces, and lines of force being called a magnetic "field." To make the number of magnetic lines represent *numerically*, as well as in mere direction, the intensity of the magnetic forces, the following device is adopted. Remembering that experiment shows that the pull (or push) which a magnetic pole experiences when placed in a magnetic field is proportional to the intensity of that field, let there be drawn as many lines to the square centimetre as there are dynes of force exerted on the unit pole. For example, if at any point it was found that the magnetic pull on a unit pole was 40 dynes, then at that place we should draw, or imagine to be drawn, 40 magnetic lines all packed within one square centimetre of sectional area. As the earth's horizontal component at London is only 0·18 (dynes on the unit pole) it follows that there would be only 18 lines passing through an area of 100 square centimetres set up vertically east and west. Returning to the definition of electromotive-force, we see that if the moving conductor cuts one magnetic line in one second) the electromotive-force generated will be of unit value in this absolute C.G.S. system of measurement. But such a unit would be ridiculously small—far too small for practical use. Measured in such units the electromotive-force of a single Daniell's cell would be represented by the enormous number of 110,000,000, and a Latimer-Clark standard cell by 143,500,000 units. Hence practical electricians adopt, as their working unit, an electromotive-force one hundred million times as great as the absolute C.G.S. unit; and they call the practical unit "one *volt.*" Hence the definition of "one volt" is that electromotive-force which would be generated by a conductor cutting across a hundred million (10^8) magnetic lines per second. The electromotive-force of a Daniell's cell is about 1·1 volts; that of Clark's standard cell 1·435 volts. The Board of Trade accepts this figure as being within 1 per cent. of the true value. The appropriate instruments for measuring volts is called a *volt-meter.* For alternating electromotive-forces, the unit legally recognized by the Board of Trade is that called in this book (see p. 631) "virtual volts."

We come then to the unit of electrical *resistance.* It is found by experiment that the current which is produced in a circuit by applying a given steady electromotive-force depends on the resistance offered by the circuit to the flow of electricity, the current being less as the resistance is greater, in accordance with the famous law discovered by Dr. Ohm.

Ohm's law, in fact, states that the current is directly proportional to the electromotive-force that is exerted in, and is inversely proportional to the resistance of, the circuit. If the symbol E stands for the number of units of electromotive-force, and R for the number of units of resistance of the circuit, and i for the current that results, then Ohm's law will be written :—

$$\frac{E}{R} = i.$$

or, the resulting current can be calculated by dividing the number of units of electromotive-force by the number of units of resistance. Another way of writing Ohm's law, which is useful when it is desired to calculate the electromotive-force that will drive any prescribed current through a given resistance, is

$$E = Ri.$$

Now suppose we had an electromotive-force equal to one absolute C.G.S. unit, and we required to produce by its means a current of unit strength as previously defined in the absolute system, it would be requisite to adjust the resistance of the circuit to a definite value; and that value would be extremely small, otherwise such a minute electromotive-force could not maintain so large a current. Nevertheless this very minute resistance would be rightly taken as the unit in the absolute C.G.S. system, for then Ohm's law would be numerically fulfilled as

$$\frac{\text{one unit of electromotive-force}}{\text{one unit of resistance}} = \text{one unit of current.}$$

But as there are already practical units of electromotive-force and of current, so there is required a practical unit of resistance to correspond. And reflection will show that the practical unit must be a thousand million times as great as the absolute unit. For then, again, Ohm's law will be fulfilled as

$$\frac{\text{one hundred million C.G.S. units of electromotive-force}}{\text{one thousand million C.G.S. units of resistance}}$$
$$= \text{one-tenth C.G.S. unit of current.}$$

The name of "one *ohm*" is given to this practical unit of resistance; and many researches have been made to determine its working value. The British Association Committee produced standard wire coils, which were long accepted as being exact *ohms*, but they are now known to be all slightly too low in resistance. In 1882 the International Congress fixed upon *the value of the ohm* as being *a resistance equal to that of a column of mercury one square millimetre in cross-section, and* 106 *centimetres long* (measured at the freezing-point of water). According to Lord Rayleigh's most careful measurements, the true ohm ought to be, not 106, but 106·3 centimetres long. The Report of the Committee of the Board of Trade adopts this more exact value and makes it the legal definition of the ohm in Great Britain.

The resistances of wires and circuits are measured in practice by comparing them with certain standard "resistance coils," sets of which are often employed arranged in "resistance boxes"; the particular instruments employed in making the comparison being of two kinds, namely, the differential galvanometers and the Wheatstone's bridge. For further information the reader must refer to the text-books on electric testing.

A rough and ready idea of the resistance called "one ohm" may be obtained by remembering that a mile of ordinary iron telegraph line offers from 13½ to 20 ohms resistance.

Another unit is required by electricians, namely, a unit of *power*, in which to express the quantity of work per second done in any electrical resistance.

To measure the rate at which work is done by a current in a wire, or in a lamp, or other thing supplied with electric power, we must measure both the *amperes* of current that are running through it, and the *volts* of electromotive-force that are actually applied at that part of the circuit, and having found the two numbers we must multiply them together. For just as engineers express power mechanically as the number of "foot-pounds" expended in a given time, so the electrician expresses electric power as the number of "volt-amperes." The more convenient name of "one *watt*" is given to the unit of electric power. Calculation shows that one "watt" or "volt-ampere" is equal to one seven-hundred-and-forty-sixth part of a horse-power.

As an example of calculation of electric power the following may be taken. It was required to ascertain the power expended in maintaining a certain arc lamp. The voltmeter showed an electric pressure of 57 volts between the terminals of the lamp, and the amperemeter showed a current of 10·5 amperes running through it. The product is 598·5 watts. Dividing by 746 to bring to horse-power, we get 0·80, or eight-tenths of a horse-power. The name *kilowatt* is given to 1000 watts. One kilowatt is slightly more than 1⅓ horse-power. As a unit of electric energy, the legal quantity recognized by the Board of Trade for the purposes of public supply, is that amount of energy supplied in an hour by a circuit delivering power at the rate of 1000 watts; or, briefly, the *Board of Trade unit* is *one kilowatt hour.*

The unit of self-induction, called by various names, *secohm*, *quad* or *quadrant*, and *henry*, is a derived unit of modern origin. Whenever a current is varying in strength, it will, if carried round a coil, set up magnetic lines which as they alter in number act inductively on the convolutions of the conductor, and set up induced electromotive forces which tend to oppose the change in value of the current. The symbol used for a coefficient of self-induction is usually L: and bears the meaning that if unit current were suddenly turned off or on in the circuit in question, the resulting amount of cutting of magnetic lines by the convolutions of the circuit would have the value L. The practical unit, to correspond with volt, ohm, &c., is taken as 10^9 C.G.S. units, or one ohm-second; or a coil will be said to have as the value of its coefficient one *henry* (or *quadrant*, or *secohm*) if, when unit current is turned on in it, the cutting of its own magnetic lines which results is as much as if 10^9 magnetic lines had been each cut once by a single convolution. If the rate of change of current at any time be expressed as $\frac{di}{dt}$, then the resulting self-induced electromotive-force opposing the change will be:—

$$= -L\frac{di}{dt}.$$

For a given form and volume of coil, the coefficient of self-induction is proportional to the square of the number of convolutions. The presence of an iron core vastly increases the self-inductive effects, but renders the coefficient of self-induction a variable quantity because of the variations in the permeability of the core. The instrument devised by Ayrton and Perry for measuring coefficients of self-induction is called a *secohmmeter*. For further details the reader is referred to treatises on the theory of electricity. He should also consult a valuable article by Mr. Kennelly in *Electrical World*, xvi. 452, 1890.

APPENDIX B.

ON WIRES.

ON p. 422 were given some data respecting the sizes of wire found suitable in practice for winding dynamos for different currents. Other data are to be found in the detailed descriptions of various machines in other parts of this book. Further, on p. 425 were given some formulæ for calculating the weights of wire needed for magnet coils. The question of heating in relation to current-carrying capacity was also treated in Chapter XV. in some detail.

A few further points may be added here founded upon information given by wire-makers, and in particular by the London Electric Wire Company.

The usual insulation for round wires of a greater diameter than No. 16 S.W.G. is a double cotton covering which increases the diameter by amounts varying from 10 to 20 mils, but which usually averages 14 mils. For smaller sizes, from No. 18 to No. 22 S.W.G., the usual double cotton covering is an addition of 12 mils. Square wire is usually double-cotton covered to 20 mils additional, or is sometimes braided. Laminated square wire, *i.e.* made of a number of narrow strips, is usually braided to about an equal amount. Since stranded wires came in for armature winding, several modes of insulating have been adopted, and one maker employs a cable of 37 wires, each No. 15 S.W.G., each single cotton covered; the whole being double-cotton covered to 16 mils additional, or braided to 20 mils. For transformer windings at high voltage a frequent practice is to wind a much thicker cotton insulation for subsequent immersion in oil. For example, a No. 23 S.W.G. wire is cotton covered to 40 mils additional, thus nearly doubling the weight of the wire.

Annexed is a table useful in magnet winding, showing the probable heating, and greatest permissible depth of winding at various amperages. It is to be remembered that 2000 amperes per sq. in. is a common density of current for field-magnets; whilst armatures run to 3000 or more.

APPENDIX B.—*continuea.*

Wire Gauge and Amperage Table.

Dimensions.				Permissible Amperage, Probable Heating, and Permissible Depth.											
				1000 Amperes to sq. inch.			2000 Amperes to sq. inch.			3000 Amperes to sq. inch.			4000 Amperes to sq. inch.		
S. W. G.	Diam.	Section (sq. inch).	Turns to 1 linear inch.	A	F	D	A	F	D	A	F	D	A	F	D
22	·028	·00062	23·81	·616	0·91	4·5	1·23	3·63	1·13	1·85	8·16	·50	2·46	14·5	·28
20	·036	·0010	20·00	1·018	1·29	3·9	2·036	5·17	·97	3·05	11·6	·43	4·07	20·7	·24
19	·040	·0012	18·52	1·26	1·53	3·6	2·52	6·02	·92	3·78	13·8	·41	5·04	24·5	·23
18	·048	·0018	16·13	1·81	1·83	3·3	3·62	7·32	·83	5·43	16·4	·37	7·24	29·3	·21
17	·056	·0024	14·28	2·4	2·14	3·2	4·8	8·56	·79	7·2	19·3	·35	9·6	34·2	·19
16	·064	·0032	12·83	3·2	2·57	3·0	6·4	10·28	·74	9·6	23·1	·33	12·8	41·1	·18
15	·072	·0040	11·63	4·0	2·90	2·9	8·0	11·6	·72	12·0	26·2	·32	16·0	46·4	·17
14	·080	·0050	10·64	5·0	3·33	2·8	10·0	13·3	·70	15·0	30·0	·31	20·0	53·3	·17
13	·092	·0060	9·44	6·6	4·29	2·7	13·2	17·2	·67	19·8	38·7	·30	26·4	68·8	·16
12	·104	·0085	8·48	8·5	4·52	2·6	17·0	18·1	·65	25·5	40·7	·29	34·0	72·3	·16
11	·116	·0105	7·69	10·5	5·07	2·5	21·0	20·3	·63	31·5	45·7	·28	42·0	81·2	·16
10	·128	·0128	7·04	12·8	5·67	2·4	25·6	22·7	·61	38·4	51·0	·27	51·2	90·7	·15
9	·144	·0163	6·33	16·3	6·50	2·4	32·6	26·8	·60	48·9	58·5	·27	65·2	104·5	·15
8	·160	·0201	5·74	20·1	7·28	2·3	40·2	29·1	·59	60·3	65·5	·26	80·4	116·4	·15
7	·176	·0243	5·26	24·3	8·06	2·3	48·6	32·2	·58	72·9	72·6	·26	97·2	120·0	·15

Stranded.															
7/22	·084	·0043	9·62	4·3	2·59	4·0	8·6	10·3	·99	12·9	23·3	·44	17·2	41·4	·25
7/20	·108	·0072	7·81	7·13	3·45	3·7	14·3	13·8	·92	21·4	31·2	·48	28·5	55·2	·23
7/18	·144	·0128	6·09	12·7	4·94	3·4	25·4	19·7	·83	38·1	44·5	·39	50·8	79·0	·21
7/16	·192	·0229	5·10	22·9	7·37	3·2	45·8	29·5	·79	68·7	66·3	·35	91·6	117·9	·20
7/15	·216	·0289	4·27	28·9	7·79	3·1	57·8	31·2	·78	86·7	70·1	·34	115·6	124·6	.20
7/14	·240	·0356	3·87	35·6	8·72	2·7	71·2	34·8	·76	106·8	78·4	·34	142·4	139·5	·19
7/13	·276	·0462	3·38	46·2	9·91	2·0	92·4	39·6	·74	138·6	89·2	·33	184·8	158·5	·19
7/12	·312	·0595	3·01	59·5	11·4	1·9	179·0	45·5	·72	178·5	102·5	·32	238·0	182·2	·18

Figures in columns marked **A** signify number of amperes that the wire carries.

Figures in columns marked **F** signify number of degrees (Fahrenheit) that the coil will warm up if there is only one layer of wire; they are calculated by Esson's modification of Forbes' rule:—

Rise in temperature (Fahrenheit degrees) = 100 × number of watts lost per sq. inch.
= 69 × sectional area × number of turns to 1 inch (at 1000 amperes per sq. inch).

Figures in column marked **D** are the depths in inches to which wire may be wound if 1 watt be lost by each square inch of radiating surface, the outside radiating surface of the bobbin only being considered.

Rule for calculating a 7-strand cable:—Diameter of cable = 1·134 × diameter of equivalent round wire.

Figures under heading "Turns to 1 linear inch" are calculated for cotton covered wires of average thicknesses of coverings used for the different guages, viz.: 14 mils additional diameter on round wires (from No. 22), and 20 mils on stranded or square wire.

Resistance (ohms) of coil of copper wire, occupying v cubic inches of coil-space, and of which the gauge is d mils uncovered, and D mils covered, may be approximately calculated by the rule:—

$$\text{ohms} = 960700 \frac{v}{D^2 d^2}.$$

ERRATA.

Page 408, line 2 from bottom, *for* "71,170,000" *read* "7,170,000."
„ 418, line 9 from top, *for* "6·51 cms." *read* "16·61 cms."
„ 461, line 17 from bottom, *for* "brush" *read* "Brush."

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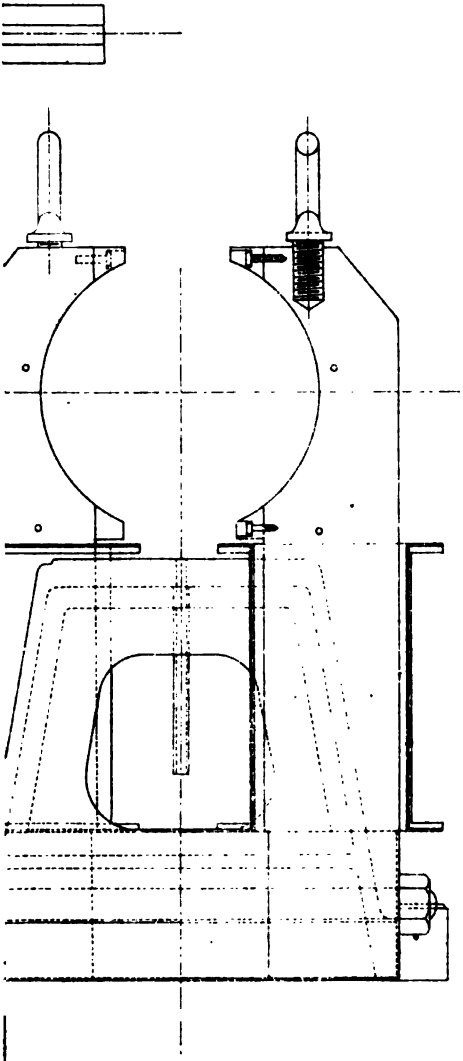

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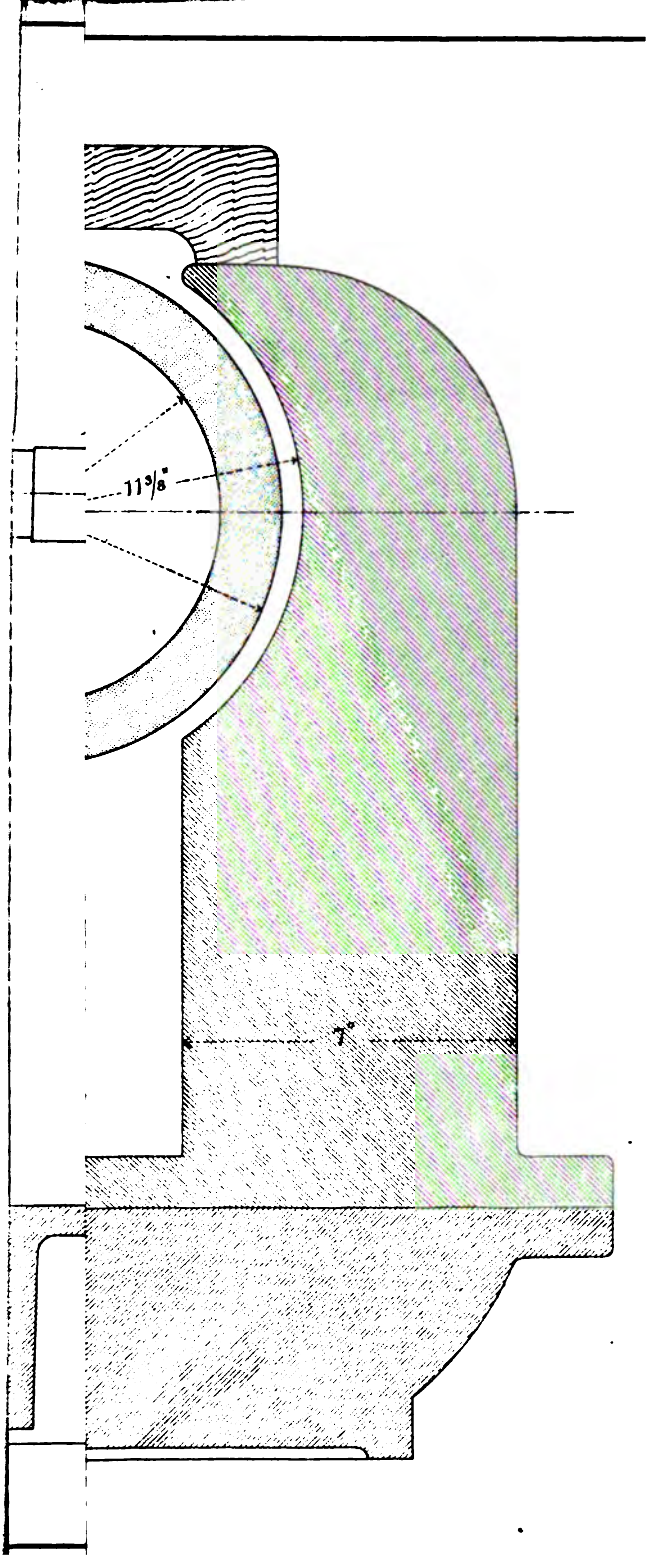
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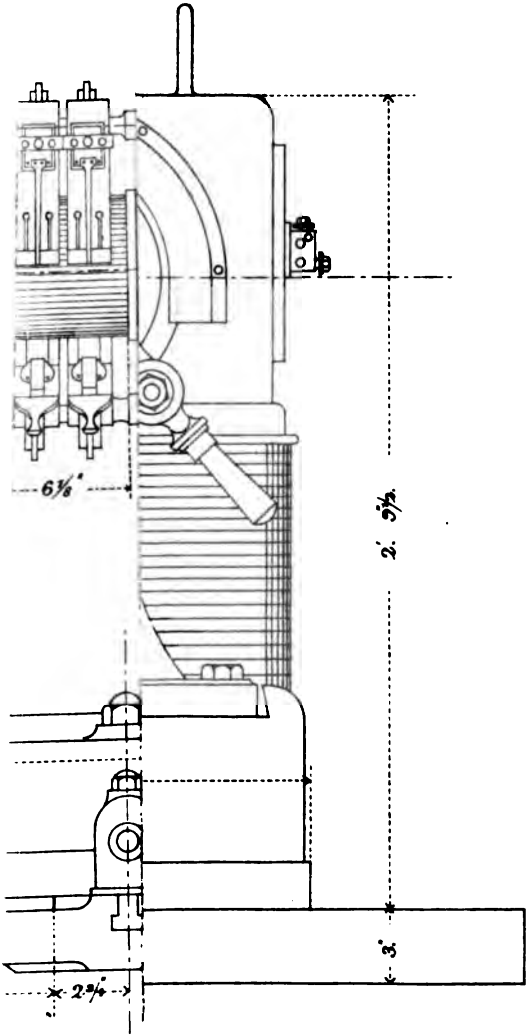

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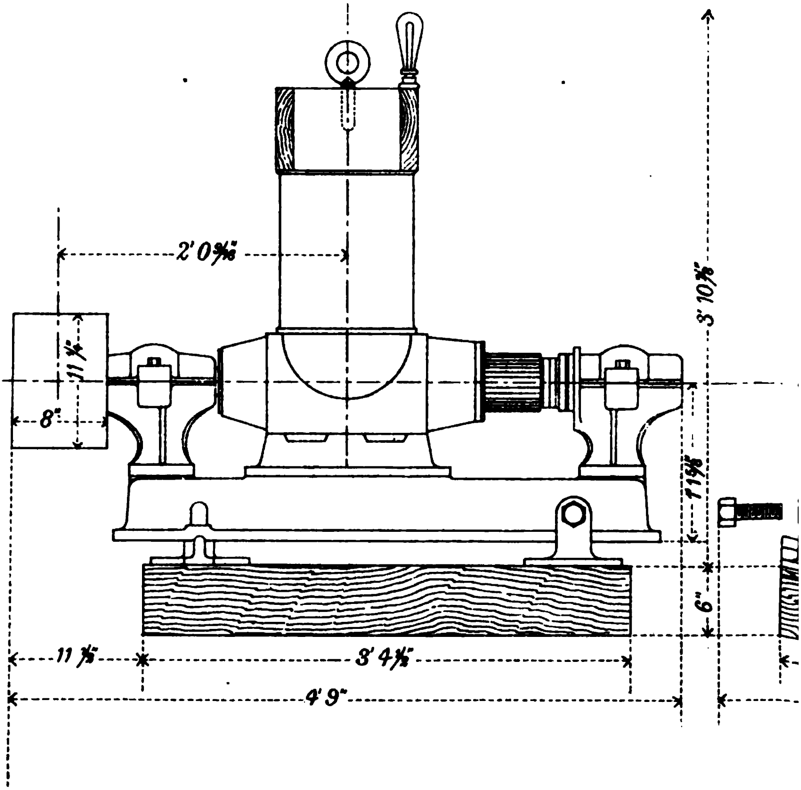

FIGS. 1 AND 2. 210 H.P. AT 450 REVS. PER MIN. OUTPUT; 107

FIGS. 3 AND 4. 21 H.P. AT 1500 REVS. PER MIN. OUTPUT; 12

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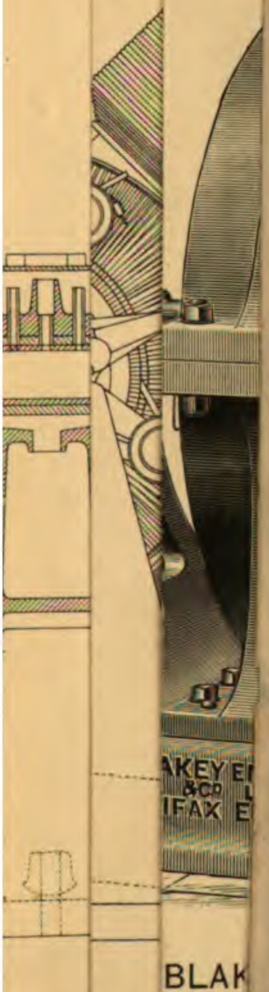

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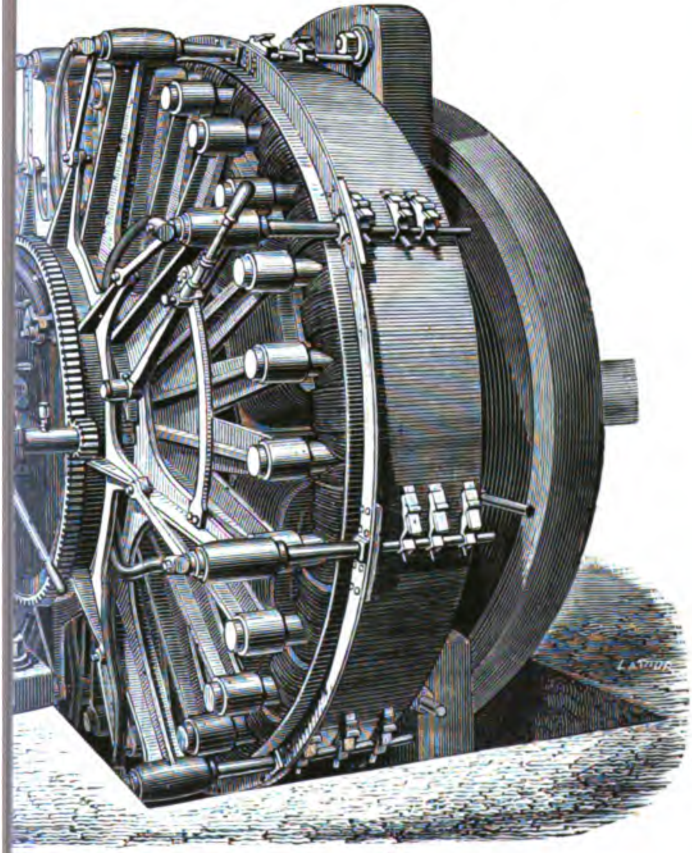
PLATE XI.

FIG. 3.



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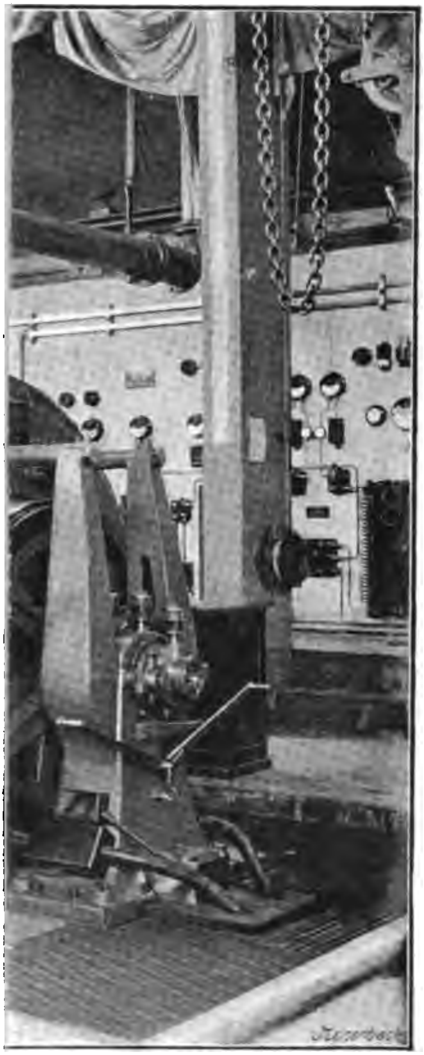

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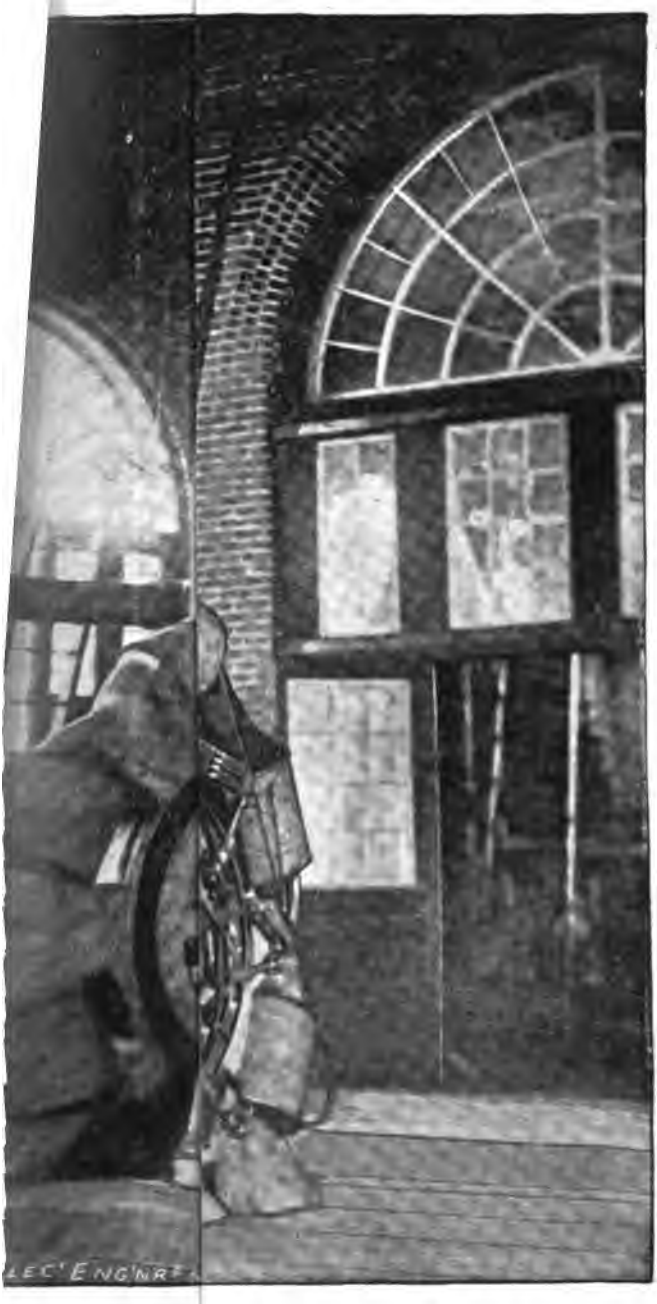

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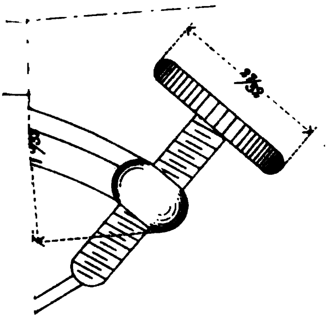

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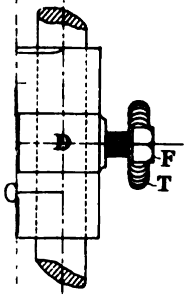

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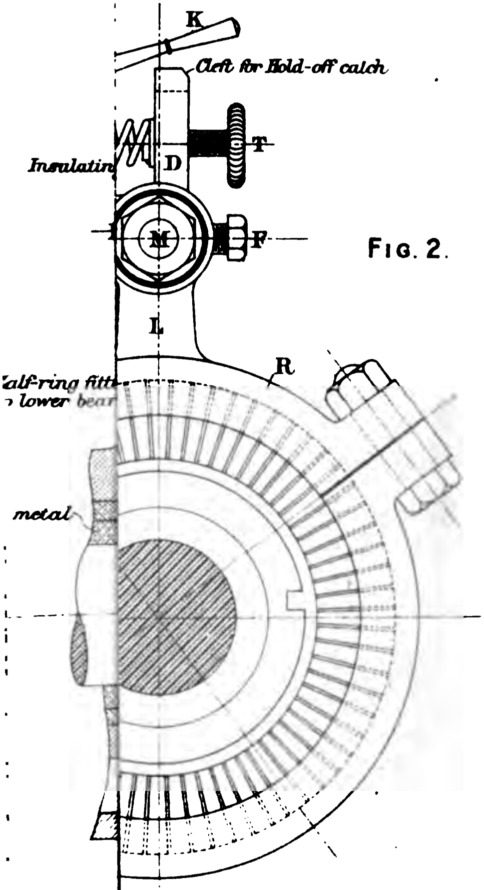

FIG. 2.

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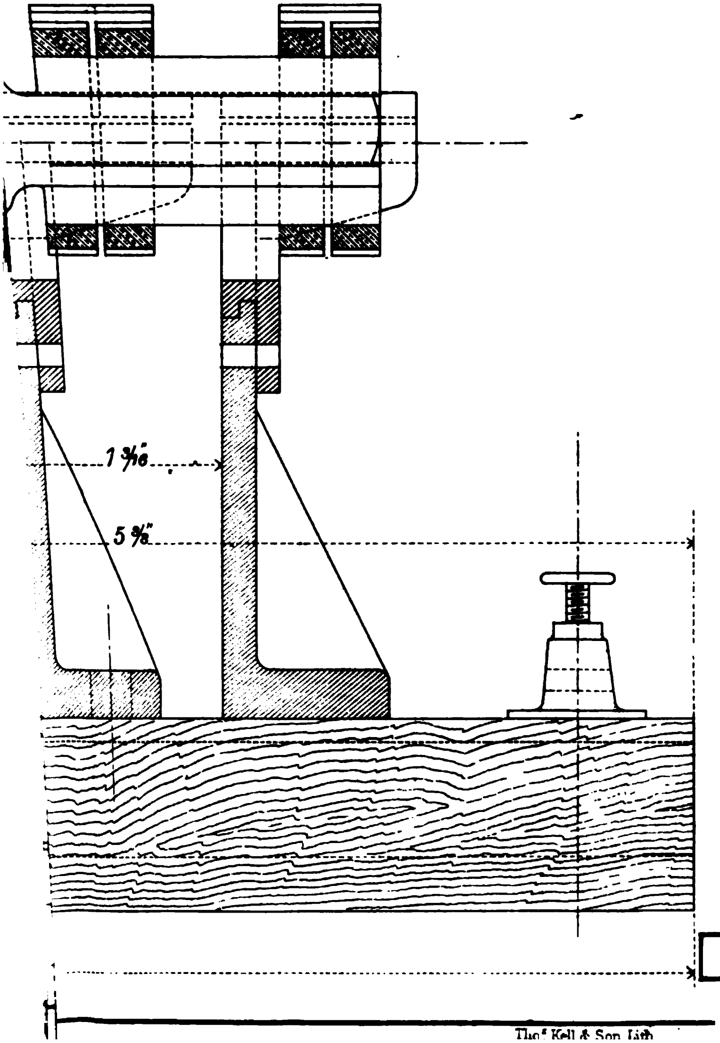

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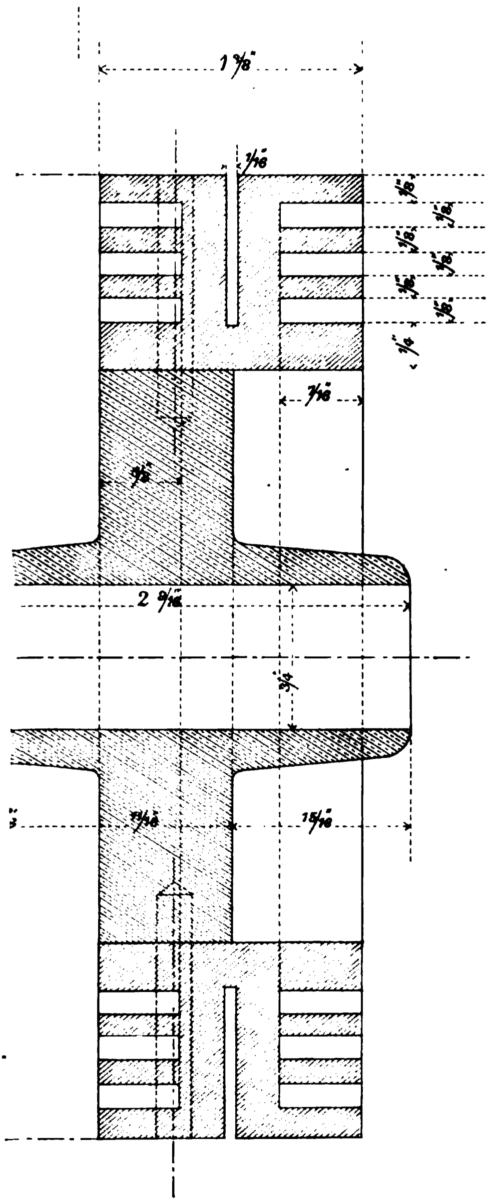

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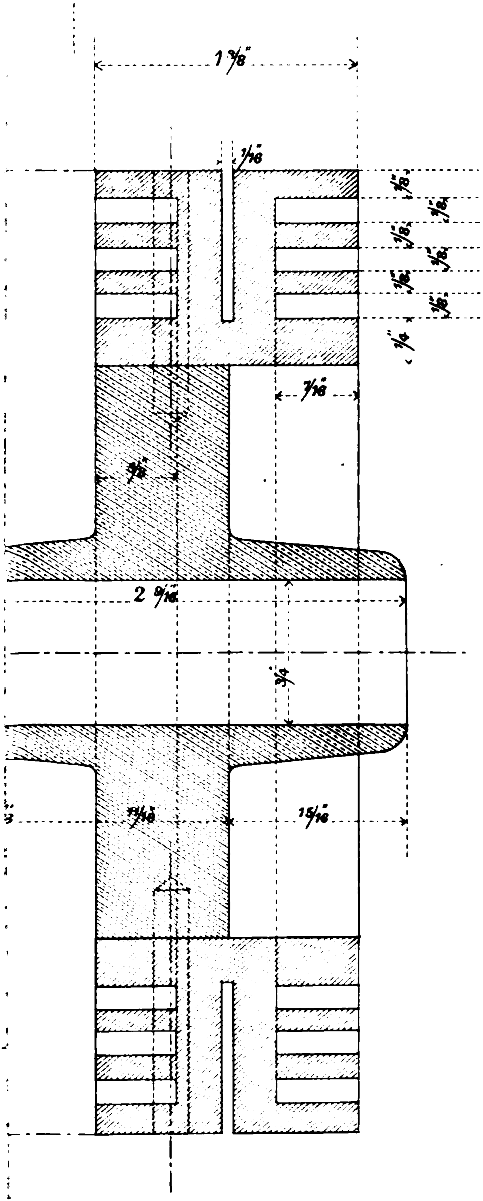

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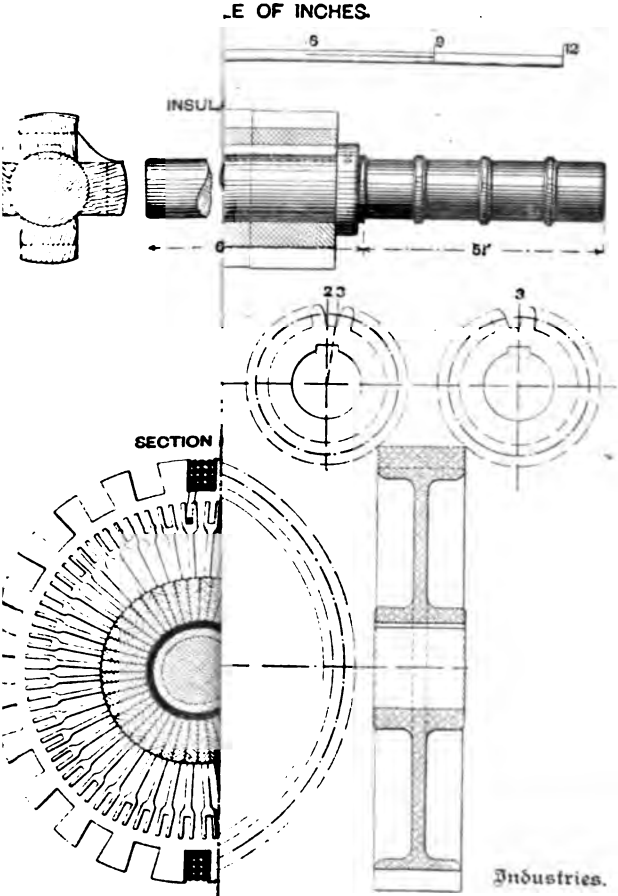

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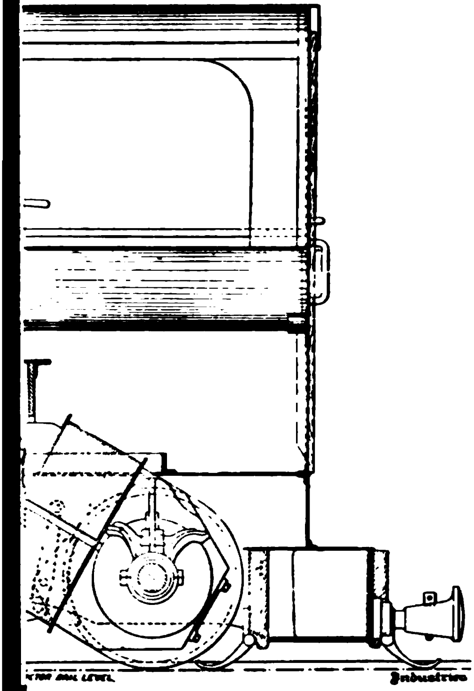

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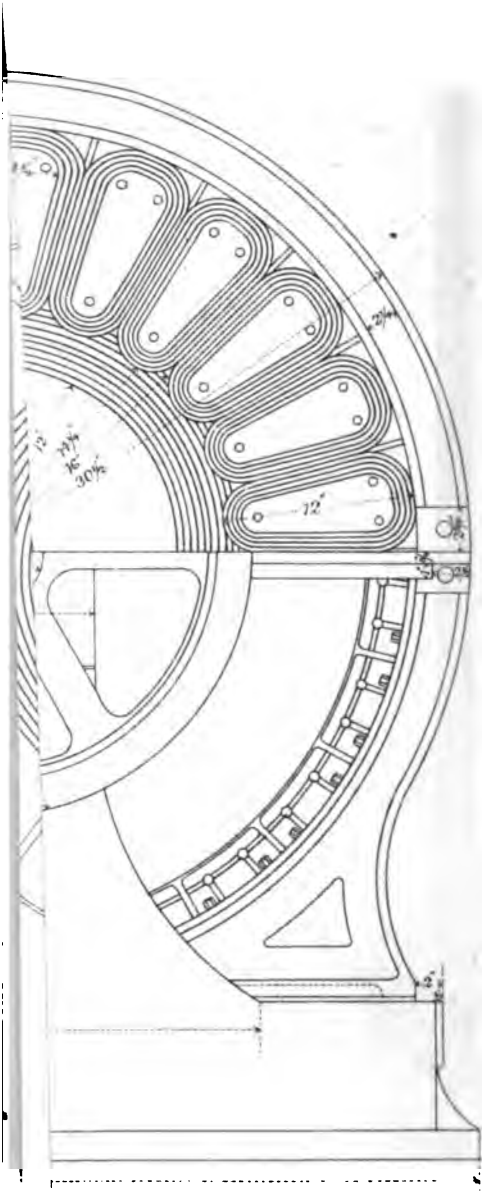
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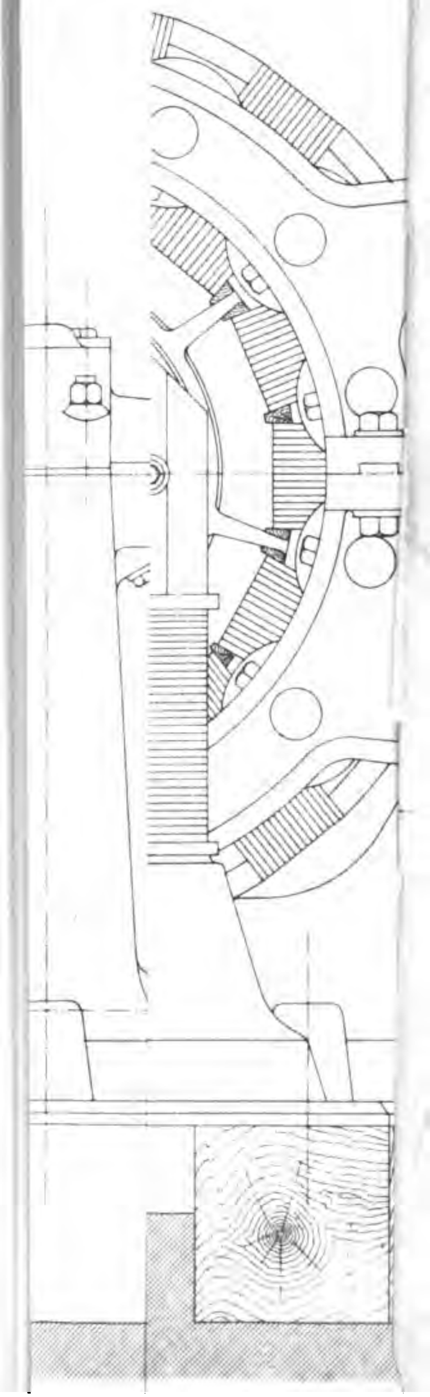

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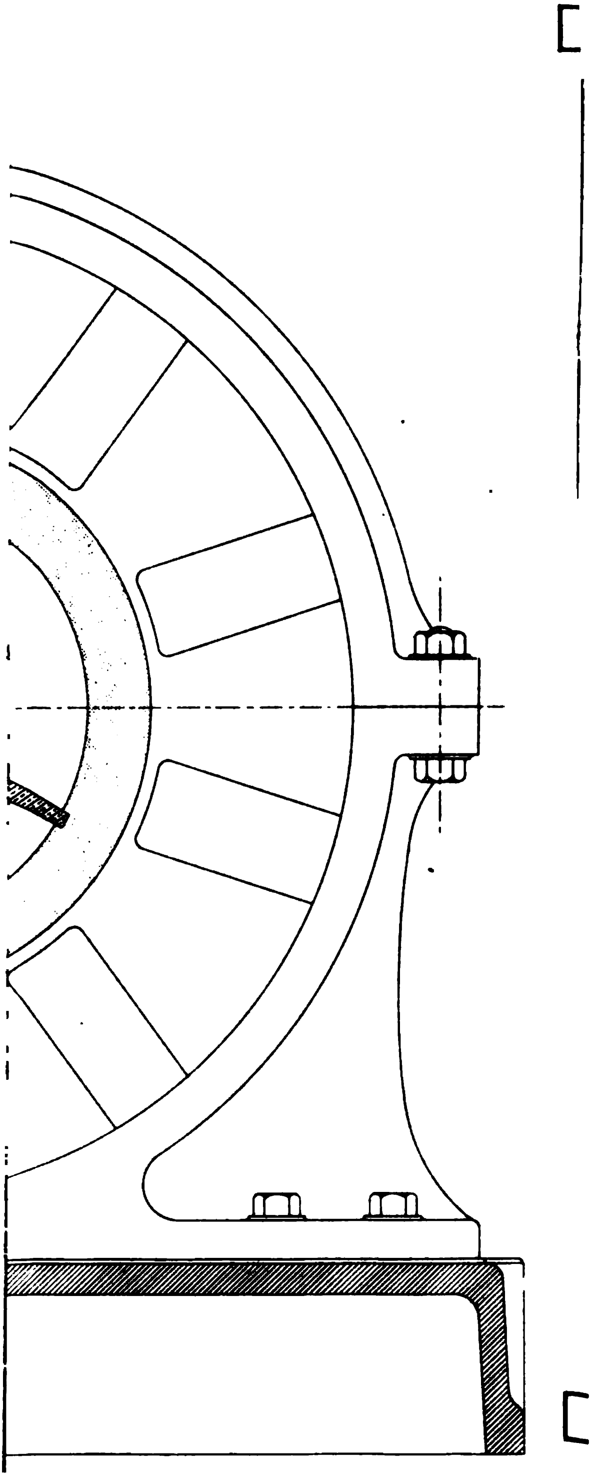

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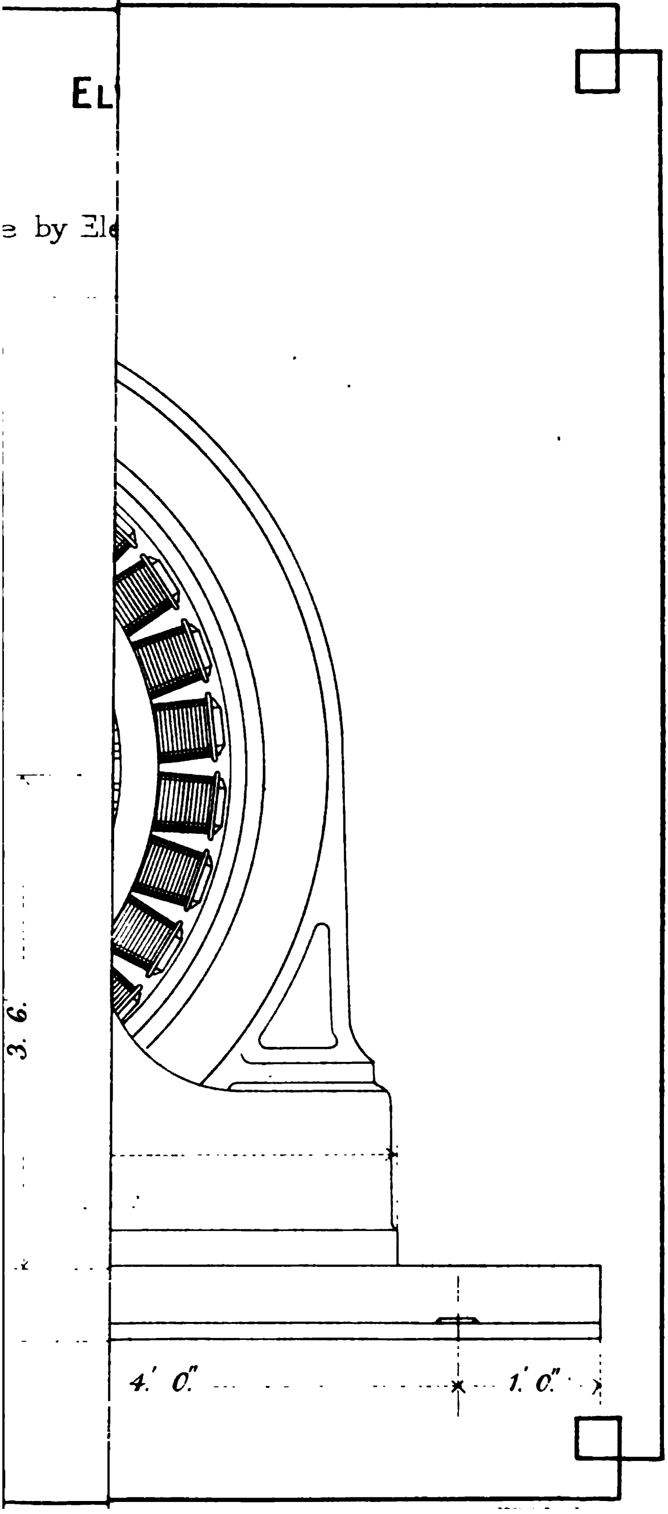

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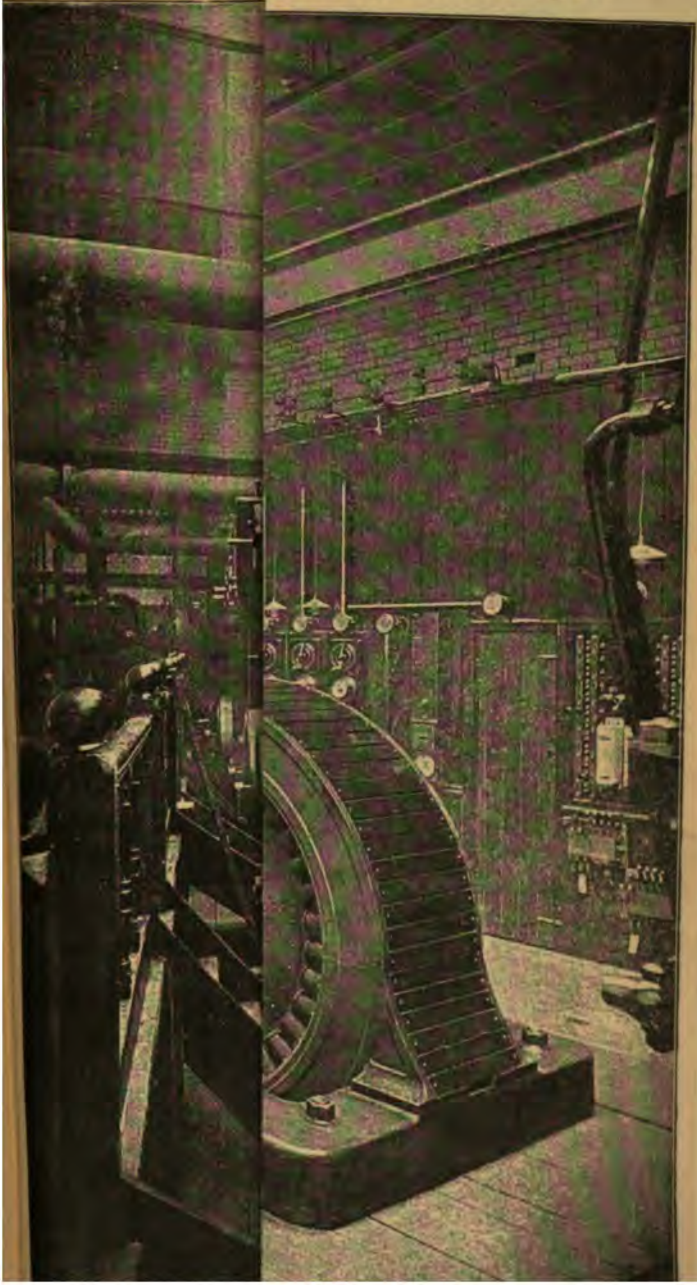

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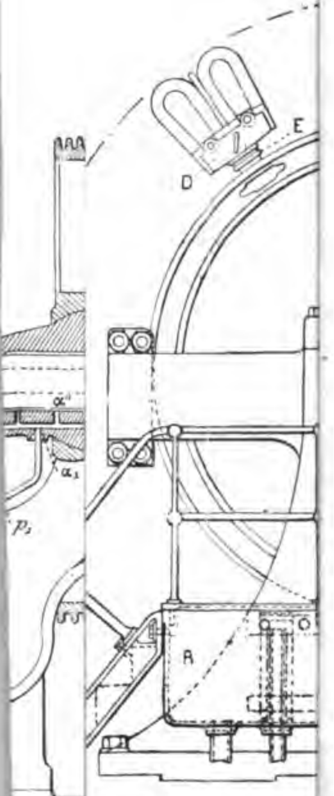

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PLATE XXVII.

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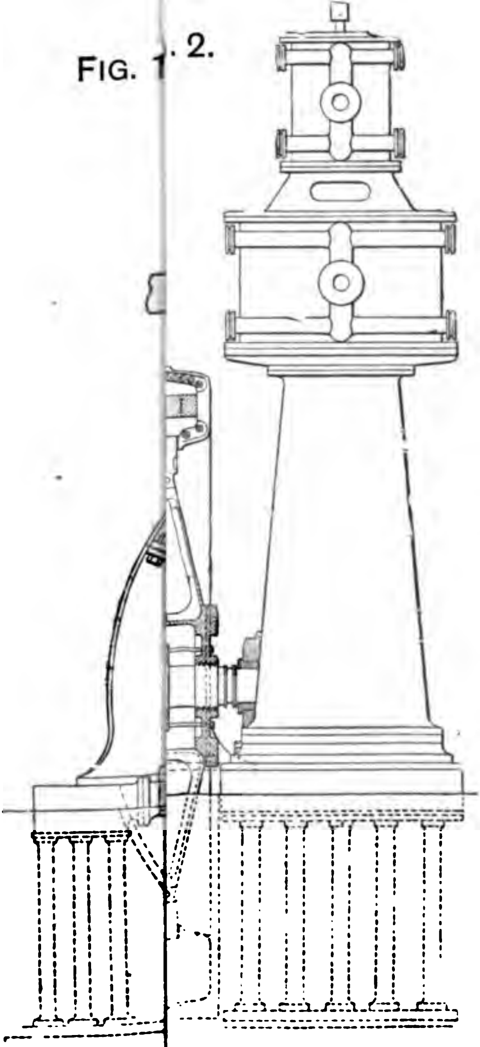

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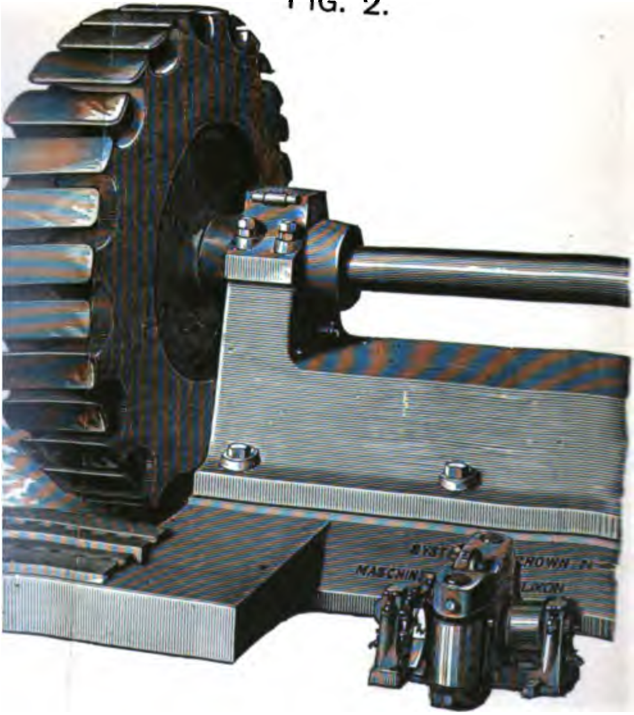
FIG. 2.



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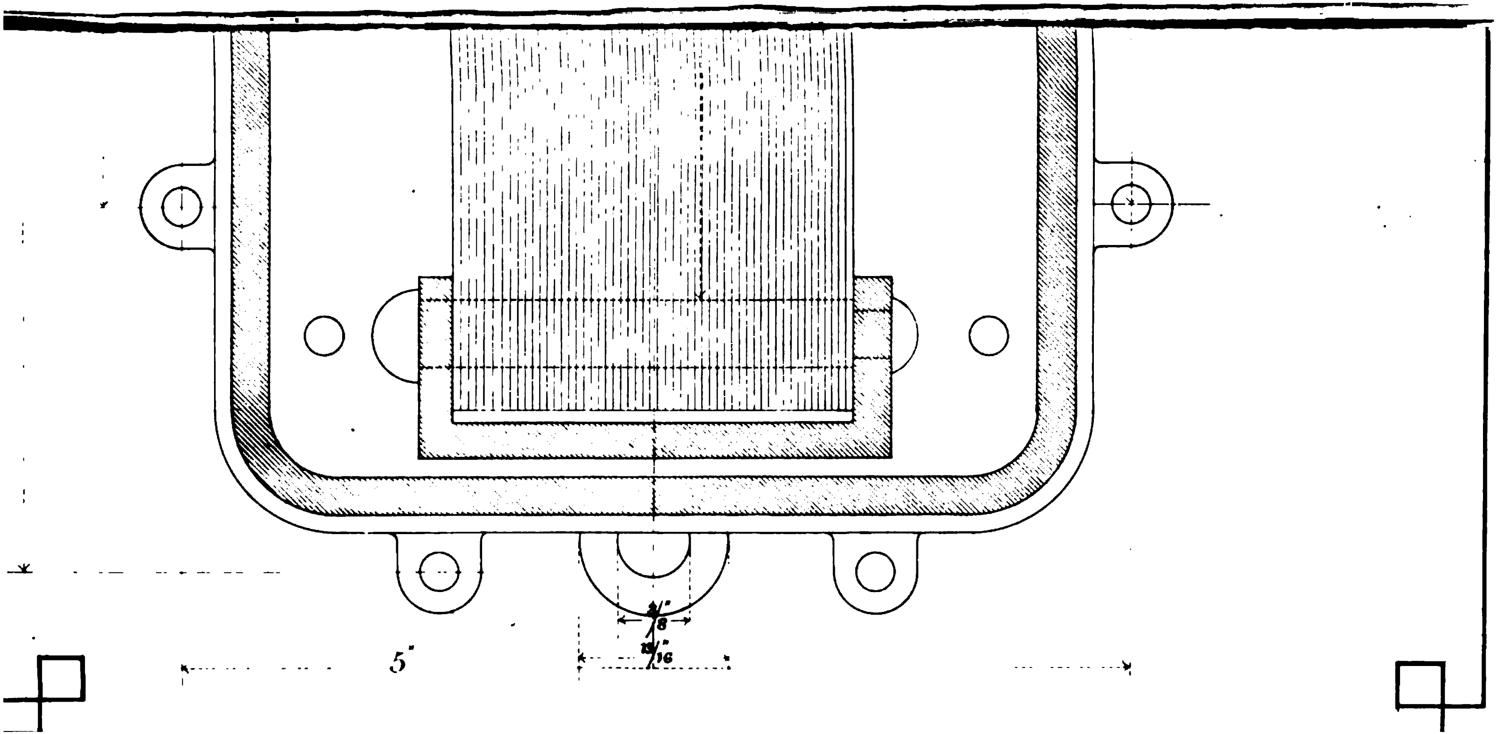

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